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Analysis of hip and lumbar spine movement during functional activity two years after Total Hip Replacement.

by
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This is for you all - Thank you

ABSTRACT

Total Hip Replacement (THR) is considered one of the commonest, mechanically effective and cost effective orthopaedic procedures performed. Routinely patients are discharged from follow-up at 1-year after surgery and little is known about hip and lumbar spine movement during function after this time.

Twenty four participants, two years after uncomplicated primary THR were compared with 24 matched healthy adults during 4 functional activities and clinical assessment of hip and lumbar spine movement. The clinical tests and hip, pelvis and lumbar spine motion during gait are presented. A 6 camera, Kinemetrix Motion Analysis system(50Hz) (MIE Ltd., UK) and a single 0.4 x 0.6m Bertec force platform (300Hz) (MIE Ltd., UK) were used.

Reliability testing of dynamic and clinical measures was undertaken and all data were tested for normality. Mean range and peak data were tested using Analysis of variance and post hoc t-tests. Data were analysed in three groups: Those after THR both the operated (THR op) and non-operated sides (THR non op) were investigated and compared to healthy individuals (THN). Alpha was set at $p<0.05$.

All physiological hip movements were greater in the THN group but only lumbar spine flexion and lateral flexion were significantly larger with extension being less.

During gait, the THR op side had significantly decreased mean hip range compared to the THR non op side and THN groups, whilst the THN side had significantly less mean range of lumbar spine motion in the sagittal plane. Sagittal plane peak hip moments were significantly larger in the THN group compared to the THR op. Considerable difference were identified in timing and range of the movement patterns in angle-time and angle-angle diagrams for the THN and THR groups.

These findings highlight possible longer term spinal complications through abnormal mechanical use and question the effectiveness of current rehabilitation after THR.

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1.0 INTRODUCTION

Approximately 15% of the female and 10% of the male UK population in the over 65 age group have radiographic evidence of moderate to severe Osteoarthrosis (OA) of the hip joint which will need treatment of some kind (Erhardt, 1995). Frankel et al (1999) report that 15.2 (12.7-17.8) per 1000 people aged 35-85 years have hip disease which was significant enough to require surgery. This amounts to a projected annual incidence of 2.23 (1.56-2.90) per 1000 of people requiring hip replacement surgery, or 46,600 operations per year in England alone.

Total hip replacement (THR) is one of the commonest (Hardy, 1993), most mechanically effective (Frankel et al, 1999) and cost effective (Garellick et al, 1998a) orthopaedic procedures performed for hip joint disease, in the National Health Service (NHS) and private hospitals in the United Kingdom today (NICE, 2000). The main reason for elective THR is to relieve discomfort and immobility caused by arthritic disease and to improve quality of life (NAO, 2000). Of all the THR surgeries undertaken the majority of these are because of primary or secondary OA (NICE, 2000).

The success rate of THR for pain relief and return of hip mobility is well documented (e.g. Keener et al, 2003; Borstlap et al, 1994). The quality of life for the recipients of the THR is undoubtedly better (Ethgen et al, 2004; Mahon et al, 2002; O'Connell et al, 2000; Knutsson & Engberg, 1999). Many authors however have shown that the majority of patients do not have return of normal function post-operatively (Kyriazis & Rigas, 2002; Andriacchi & Hurwitz, 1997; Kirwan et al, 1994; Skinner, 1993; Perrin et al, 1985; Murray et al, 1976 etc). Bhave et al (2005) examined 67 people with joint replacement to identify problems after total hip replacement, finding that 54% had weak hip abductors, 14% had leg length discrepancies and 6.7% had mal-alignment of either knee or foot. Soft tissue problems occurred in people early post operation (2-2.5 months) and alignment issues at approximately one year.

Most researchers assess functional return either by analysis of the gait pattern (Andriacchi & Hurwitz, 1997; Murray et al, 1972) or the energy efficiency of gait (Waters & Mulroy, 1999; Loizeau et al, 1995; Pugh, 1973). Few have looked at other activities of daily living (MacWilliam et al, 1996) or quality of life measures (Ethgen et al, 2004; Borstlap et al, 1994) or patient questionnaire (Söderman et al, 2001a; Espehaug et al, 1998; Kirwan et al, 1994). It is unclear why patients with good recovery of physiological movement and diminished pain, do not return to full function. Skinner (1993) with others suggests that the lack of recovery may be due to: poor preoperative functional mobility (MacWilliam et al, 1996), type of joint replacement and lack of patient adaptation to their new post-operative mobility all contribute (Andriacchi & Hurwitz, 1997). It is hypothesised that patients modify their gait pattern to reduce the risk of failure of the prosthesis (Hurwitz et al, 1992; Ajemian at al, 1997; Andriacchi & Hurwitz, 1997). Kili et al (2003) compared the Harris hip score values of 167 people awaiting THR from the time of going on the surgical waiting list to that at two weeks before surgery, (mean 330 days). The results indicated a highly significant ($p<0.001$) decrease in the Harris hip score (mean 8.9) indicating that there had been a large decrease in hip movement and functional performance over the waiting period.

There is little doubt that decreased preoperative performance of either specific hip or general function has a significant impact on post-operative outcome but it is unknown whether this impacts on long term post-operative performance. Whatever the cause, patients after THR do not regain a normal gait pattern or biomechanics of walking, and have self reported problems with general function up to one year post-operation (MacWilliam et al, 1996).

Most orthopaedic surgeons in the UK stop reviewing their patients at six months after surgery with only 24% of consultants continuing reviews for the patients lifetime at either yearly or five-yearly intervals (NAO, 2003), despite the results from research which report ongoing problems. It is highly unusual for the orthopaedic follow up to do anything more than review clinical signs e.g. prosthetic condition, pain level or hip range of movement. Given that Kyriazis & Rigas (2002) report major change up to 1 year post surgery and that at 8-10 years post surgery temporal parameters have not reached control levels, then 5 year follow up may be insufficient. Murray et al (1975) also report biomechanical changes up to two years post hip replacement surgery.

Biomechanical review of walking is only undertaken for specific research projects and limited in most cases to hip and knee joint function (Murray et al, 1975). Although there is strong evidence of altered interaction between the hip and lumbar spine with injury or disease (Gracovetsky et al, 1990), there is very little evidence of biomechanical review of these anatomical areas during function following THR. Murray et al in 1971 suggested that

> *"If the motion or load bearing capacity of the hip joint is compromised alterations in the motion & loads at the other lower extremity joints and back may occur".* (Murray et al, 1971)

Hurwitz et al (1997) and Hulet et al (1996) confirmed these views suggesting that pain and other clinical symptoms may develop at other joints as a compensation for hip disease by altering the demands on surrounding musculature and soft tissue.

There are known alterations in the biomechanics of the hip during walking after THR. It can be predicted that there will be concurrent deficit in the biomechanical changes in other anatomical areas or when performing other functions. Functions which are known to cause problems to people with hip OA or after THR e.g. sitting to standing, bending forward or stepping up (Munin et al, 1995; Zavadak et al, 1995) have yet to be analysed in terms of biomechanical modifications.

This thesis presents the results of work over the last nine years exploring the issues around post-operative hip and lumbar spine function of patients with total hip replacement. The work was undertaken in the Human Motion Laboratory at the University of East London, which was established in 1996. Part of this work was the setting up and validating the use of the Kinemetrix Motion Analysis System ® and

Bertec force platform ® (MIE Ltd., Leeds UK) and resulted in the completion of the paper, Thornton et al (1998).

1.1 AIMS

This study investigated the patterns of hip and lumbar spine movement in patients at two years after total hip replacement, and a group of healthy normals in the same age band and gender distribution, during four functional activities. The activities investigated were walking, sitting to standing, bending forward in sitting and bending forward in standing, only the data for walking will be presented in this thesis, due to the volume of data collected. To compare the patterns of movement generated during walking, this study explored the use of movement diagrams for the hip and lumbar spine to see if they are comparable between the THR and control groups. Passive physiological movements of the hip and lumbar spine data were also measured. General data regarding THR and functional activity were also gathered by open questionnaire.

1.2 NULL HYPOTHESES

The null hypotheses are:

H_{O1} Clinical hip and lumbar spine range of motion (degrees) of the THR group will not be significantly different ($p<0.05$) to those in the control group, measured by the universal goniometer, inclinometer or tape measure.

H_{O2} Significant mean range of kinematic and kinetic differences ($p<0.05$) will not be present in hip, pelvis and lumbar spine motion between the THR group and their normal controls during walking, measured by Kinematic motion analysis system and the Bertec force plate.

H_{O3} Significant mean range of kinematic and kinetic differences ($p<0.05$) will not be present in hip, pelvis and lumbar spine motion between the THR group and their normal controls at heel strike, measured by Kinematic motion analysis system and the Bertec force plate.

H_{O4} Significant mean range of kinematic and kinetic differences ($p<0.05$) will not be present in hip, pelvis and lumbar spine motion between the THR group and their normal controls at toe off, measured by Kinematic motion analysis system and the Bertec force plate.

H_{o5} Significant mean range of kinematic and kinetic differences ($p<0.05$) will not be present in hip, pelvis and lumbar spine motion between the operated side and the non operated side of the THR group during walking, measured by Kinematic motion analysis system and the Bertec force plate.

H_{o6} Significant mean range of kinematic and kinetic differences ($p<0.05$) will not be present in hip, pelvis and lumbar spine motion between the operated side and the non operated side of the THR group at heel strike and toe off, measured by Kinematic motion analysis system and the Bertec force plate.

Although not tested statistically it is also assumed that hip, pelvis and lumbar spine movement patterns in the THR group will not show substantial differences to those of the normal controls during walking measured by Kinematic Motion analysis system and the Bertec Force plate and that there will be no significant differences in the general functional performance between the THR group and their normal controls, measured by questioning.

2.0 LITERATURE REVIEW: Part 1

BACKGROUND TO TOTAL HIP REPLACEMENT

The literature review is divided into three chapters (Chapter 2, 3 and 4). Chapter 2 deals with the issues surrounding osteoarthrosis (OA), and Total Hip Replacement (THR), and will also give insight into the development of the THR and the main outcomes observed in this area today. Chapter 3 reviews the specifics of the hip and lumbar spine anatomy and kinesiology. Finally, Chapter 4 discusses the biomechanical problems related to functional activity and the recovery of movement after total hip replacement.

2.1 OSTEOARTHROSIS OF THE HIP

2.1.1 Pathology

Osteoarthrosis (OA) of the hip joint is one of the commonest problems in the over 60's in the UK. OA can develop from either primary or secondary causes with trauma or juvenile joint disease being the main underlying basis of altered alignment, which predisposes the joint to secondary OA.

Whether primary or secondary there is little debate on the pathology of OA, which is regarded as the gradual onset of wear and tear of the joint surfaces that results through five stages of disease:

- Articular cartilage breakdown
- Synovial irritation
- Remodelling
- Eburnation of the bone with possible cyst formation
- Joint disorganisation (Dandy & Edwards, 2003, p 284)

All synovial joints have a covering hyaline articular cartilage, which distributes load over a wide area (Ateshian et al, 1994) and allows movement of the joint without friction (Mow & Ateshian, 1997). In the young adult, there is normally 1mm to 6mm thickness of cartilage in the joints but this reduces because of water reduction with age. Water constitutes the main component (80%) of cartilage (Nordin &

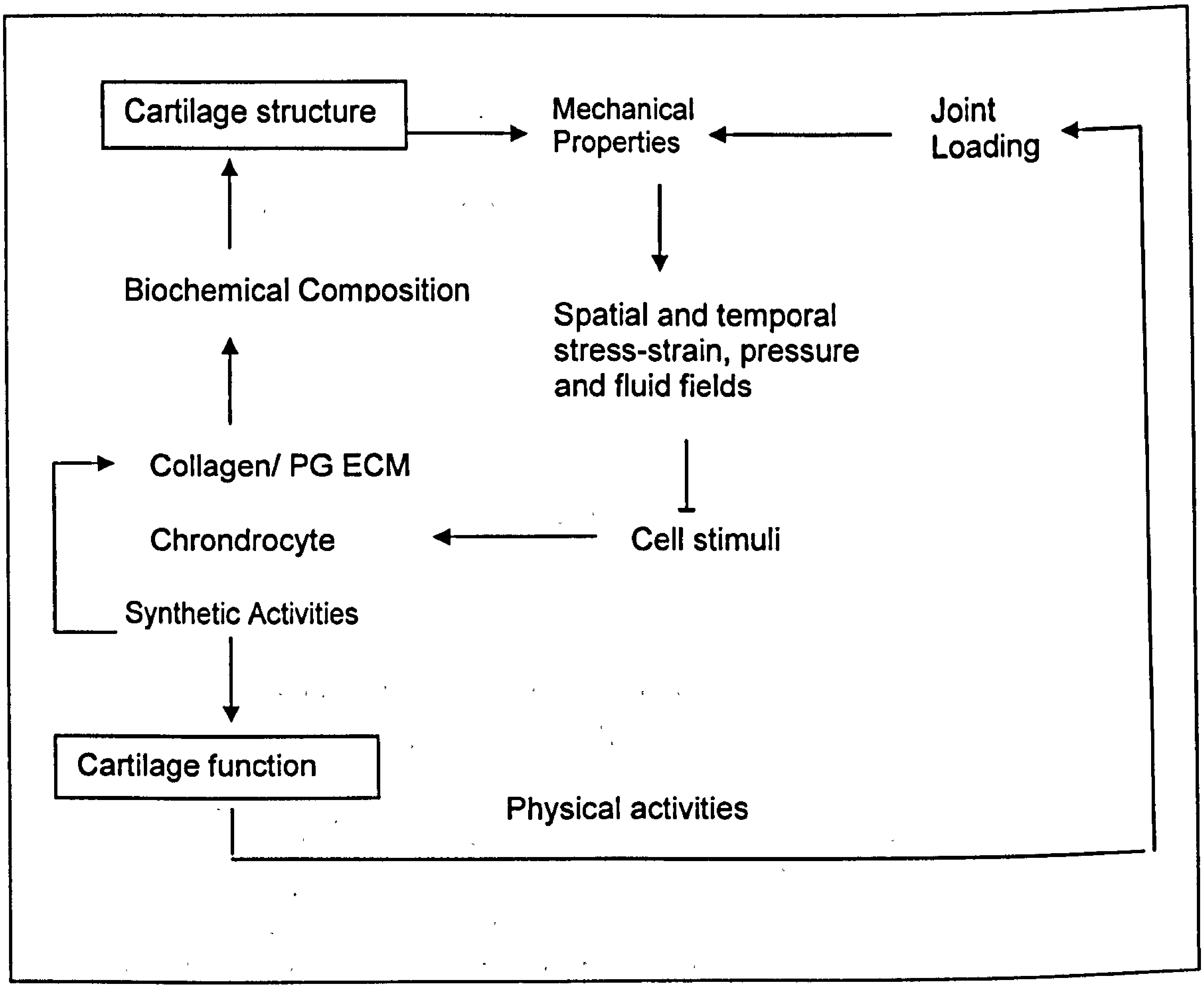


Figure 2.1 “Flow diagram of the events mediating the structure and function of articular cartilage. Physical activities result in joint loads that are transmitted to the chrondrocyte via its extracellular matrix (ECM). The chrondrocyte varies its cellular activities in response to the mechano-electrochemical stimuli generated by loading of its environment. The aetiology of OA is unclear but may be traced to intrinsic changes to the chrondrocyte or to an altered ECM (e.g. resulting from injury or gradual wear) that leads to abnormal chrondrocyte stimuli and cell activity.”

(Nordin and Frankel, 2001)

Frankel, 2001). During weightbearing the joint is cyclically loaded with compressive forces which squeeze the water out of the cartilage reducing it by up to 70% depending on the site. This process allows both lubrication of the joint and nutrition of the cartilage which is avascular and has no lymphatic control or nerve supply (Nordin & Frankel, 2001). It is thought that excess loading across a joint causes the trauma which may give rise to the initial symptoms of OA see Figure 2.1.

The force across the normal hip joint can reach to over three times body weight when standing on one leg with the pelvis straight, but this alters when the body changes position (Nordin & Frankel, 2001). A force of between 4-7 times body weight occurs across the hip joint on walking in men and 3-4 times in women (Paul, 1967; Paul & McGrouther, 1975). Van den Bogert et al (1999) reported forces of up to eight times body weight going across the hip joint during running and skiing. With excessive degree of force going across the joint with repeated loading and overuse, the joint cartilage starts to break down over time.

In OA, the articular cartilage gradually breaks down giving a roughened surface to the joint with pieces of tissue breaking off into the joint space. The cartilage pieces are absorbed by the synovium and cause a concomitant inflammatory reaction. This gives rise to swelling, heat, stiffness and pain and provide the first signs of the disease process. The pain is worse after prolonged periods of rest or after exercise/ overuse or if the joint is held in one position for a long time; movement helps to lubricate the joint surfaces so reducing tissue inflammation (Dandy & Edwards, 2003). Articular cartilage cannot repair itself but can be partially replaced by fibrous cartilage (Salter et al, 1980), however fibrous cartilage does not have the same tensile properties as articular cartilage to withstand the normal stress loading and will be damaged more quickly. Additional tissue flakes off into the joint space and the damage cycle re-establishes itself. As the cartilage erodes so the joint space becomes narrower and in time there is shortening of the limb. Once the deeper layers of cartilage become damaged the subchondral bone is exposed, becoming the new weight bearing surface.

Bone becomes polished and eburnated and microfractures occur resulting in increased pain and swelling (Dandy & Edwards, 2003). As the articular surface becomes uneven due to the loss of cartilage and bone, there is irregular loading of the joint periphery producing eroded areas: cysts, sclerosis, whilst excessive loading stimulates new bone growth (Wolff's Law), producing osteophytes (Nordin & Frankel, 2001). Osteophytes develop at the joint margins and these cause added trauma to the joint capsule, ligaments and surrounding tissue (Dandy & Edwards, 2003). As the joint space becomes narrower and the ligaments and capsule become involved, normal physiological movement is restricted and joint biomechanics are compromised resulting in deformity. The common result at the hip joint is limitation of extension, abduction and rotation with shortening of the head and neck of the femur. The hip joint is held in a flexed position, which results in a concomitant weakening of the opposing muscles (extensors, abductors and rotators).

2.1.2 Risk factors

Progression of the OA process depends on a number of differing risk factors. The general risk factors for OA for any joint, include obesity, joint overuse, joint hypermobility, hereditary factors, and other diseases or trauma (Cheng et al, 2000a; Erhardt, 1995). Following a prospective study over 10 years of 16,961 people (male and female) in Dallas, the researchers found no relationship between the onset of hip and knee OA and level of activity in those aged 50-87 (Cheng et al, 2000a). There was however a significant positive relationship between high levels of activity and the onset of OA in young men (20 - 49 years), but no relationship for young women. Karlson et al (2003) in a questionnaire study of 93,442 women demonstrated a strong significant correlation ($p=0.0001$) between Body Mass Index (BMI) and likelihood of needing a THR. Women with the a BMI of ≥ 35 kg/m^2 were 2.6 times more likely to need a hip replacement than those with the lowest BMI < 22 kg/m^2. However the highest risk factors were found between the BMI at 18 years of age (7.4 times more likely) and age: those over 70 years of age were 9 times more likely to have a hip replacement than those younger than 55 years. Amin et al (2006) in their review on obesity and joint replacement found no other significant predictors of hip replacement.

The greatest causative factor of primary or secondary OA at the hip joint is altered mechanics due to developmental abnormality or trauma, which causes superolateral bone loss with potential migration of the femoral head (Erhardt, 1995). The greater the trauma, or the more complicated the initial disease process, the higher the risk of developing secondary OA (Dandy & Edwards, 2003). Other factors, which influence primary OA of the hip specifically, are alterations in the female sex hormones, onset of symptoms in later years and an atrophic radiographic pattern (Erhardt, 1995). Gelber et al (1999) in a large prospective study of 1,180 males found no relationship between high BMI and the onset of hip OA, but that was not the case for development of OA of the knee.

Radin et al (1991) give convincing evidence that the main aetiology of degenerative disease is mechanical and not inflammatory. Given this basis, Tetsworth and Paley (1994) suggest that evidence from the orthopaedic literature substantiates the cause and effect relationship between malalignment and arthrosis (early OA). Chao et al (1994) state that "*the horizontal orientation of the joint lines at the hip, knee and ankle is an essential anatomic determinant for all weightbearing functions*". Malalignment, as defined by alteration in the mechanical axis of the limb, has been shown to alter the stress distribution across joints in the lower extremity (Chao et al, 1994). This may in turn lead to early signs of arthrosis leading to the diagnosis of Osteoarthrosis, because of its almost spherical ball and socket shape (Tetsworth and Paley, 1994).

Of the lower limb joints the hip is more able to deal with alterations in alignment but mechanical alterations of the femur will have resultant effects at the hip, knee and ankle (Chao et al, 1994). These researchers studied lower limb alignment in 127 normal adults, demonstrating no change in the lateral proximal femoral angle 91.5±4.6° to 92.7±4.9° (young and older women respectively) or in the angle of inclination: the angle between the proximal femoral joint orientation to the mechanical axis of the femur, in women with advancing age. In men, however there was a significant change with age showing a varus increase in the angle with a change from 89.2±5.4° in younger men to 94.6±5.2° in older. The change with age in the male population to 94.6±.2° brings the lateral proximal femoral angle to a similar value to that of the female population (92.7±4.9°). It is unclear why this change should occur in men and not women but it may be dependent on the size of the original femoral angle or change in the varus angle of the knee in men with age.

2.1.3 Aetiology

Fear et al (1997) explored the prevalence of hip problems in a North Yorkshire population aged 55 years and over, using a multistage stratified random sample postal questionnaire. The questionnaire included the Index of severity of Osteoarthrosis of the hips and knees (Lequesne et al, 1987) which is a self ranking scale identifying joint problems. Those with a score of 14 or over were regarded as having sufficient hip problems to warrant THR. Fear et al (1997) reported that 13.5 per 1000 respondents (95% CI 12.4-14.7) indicated hip problems that were severe enough to be eligible for THR surgery, with the largest numbers being in the over 75 year old category (20 per 1000 [15.4-25.4]). The overall incidence of males to females is 1:2 but over the age of 75 this increased to 1:3. There was no indication of the underlying pathology but the authors indicate that 98% of those with hip problems had seen their GP in the last year and the majority of these had OA.

These results are slightly lower than those reported by Frankel et al (1999) who identified 15.2 (range 12.7-17.8) per 1000 people aged 35-85 years having hip disease which was severe enough to require surgery. Again a self reported questionnaire was utilised however a second stage clinical examination was also undertaken. The questionnaire used in Frankel's study was a screening tool, but the main identifier of hip problems was the clinical examination, which may have influenced the outcome. The other main difference arising from these two studies was age. Frankel et al (1999) looked at an age group from 35-85 but Fear et al (1997) only looked at those over 55 years. The extended age range may account for the larger reported number of hip problems in the Frankel study as younger people with trauma or developmental hip disease may have been included. Gender was not significantly different between these studies although there were slight population differences, 65% of those in the Fear study came from a rural environment compared to those studied by Frankel et al (1999).

Both studies indicated that a greater number of females have hip problems than men, although the Frankel study (1:1.6) had a smaller ratio of males to females than the Fear study (1:2). Both studies reported that the gender ratio increases with age to a maximum of 1: 3 in over 75 year olds.

Therefore primary OA hip is more likely to be seen in seen in women particularly in later life (>75 years) with a family history of OA. Secondary OA can occur in anyone who has had previous hip joint problems through trauma or disease and these people may report problems at an earlier age.

2.2 TOTAL HIP REPLACEMENT SURGERY AND OUTCOMES

As stated earlier, Total Hip Replacement (THR) has been reported as one of the commonest and most effective orthopaedic procedures performed for hip joint disease today (NICE, 2000). The University of Leeds, NHS Centre for Reviews and Dissemination (1996) state that THR surgery is highly cost effective. More than 90% of patients maintain reasonably good clinical outcomes at 10 – 20 years after surgery. As the main reason for elective THR is to relieve discomfort and immobility caused by arthritic disease and to improve quality of life, the statistics above indicate a highly effective treatment.

This section will explore a brief history of hip replacements and the main issues concerning THR today.

2.2.1 History of THR

The derivation of the total hip replacement as we know it today started from the developmental work of John Charnley in the 1950's. The basic structure of all future hip replacements was modelled on this work. This section explores the history of

THR leading to the use of the Charnley and Stanmore hip replacements, as the Stanmore was the type of prosthesis used in this study and the Charnley was the original gold standard design of THR.

By 1959 the first total hip replacement had been established and inserted (Charnley, 1972). Charnley's design used a metal femoral head on a high density polyethylene acetabulum fixed with acrylic (Polymethylmethacrylate) cement (Charnley & Kramangar, 1969; Charnley, 1964) to give a low friction ball and socket joint. From 1962, insertion of the Charnley THR in human subjects was well underway.

Although Charnley is regarded as the founder of hip replacements and the prosthesis is still regarded as the 'gold standard' (Clift & Rowley, 1992), several other surgeons and engineers had been working towards the same goal. These included Gluck and his work on the ivory ball and socket joint or wooden hip joint but few of these left the laboratory. In 1895 Robert-Jones tried interpositional arthroplasties, where gold foil was inserted over the cut end of the neck of the femur, which then articulated with the acetabulum. This surgical procedure did not succeed due to failure of the foil (Wytch et al, 1989). Smith-Peterson placed a metal cup between the acetabulum and the head of the femur in the hope that this would form a new mould for the hip. Viscaloid (1923), Pyrex glass (1933) and Bakelite (1937) were all tried as inserts between the femoral head and the acetabulum but these materials failed because they could not withstand the forces generated across the hip joint (Wytch et al, 1989).

In 1938, Philip Wiles designed the first total stainless steel arthroplasty with a metal bolt holding the femoral component in place (Clift & Rowley, 1992). Six replacements were undertaken but follow up information on the outcome of this groundbreaking work is available. The basic design of the total hip replacement had been developed by Wiles (Clift & Rowley, 1992) but it was the Judet brothers in 1946 who introduced the use of the acrylic implant (Wytch et al, 1989). Some of these prostheses lasted for up to five years before they were deemed unsuccessful, because the acrylic stem was not strong enough to withstand the forces across the hip joint.

Both Moore and Thompson in the early 1950s developed hemi-arthroplasties where only the femoral component was replaced. Designed from cast cobalt chrome alloy these components relied on either a tight fit or bone ingrowth to stabilise the stem of the prosthesis. Results were good in the early stages but unfortunately the metal head tended to bore through the acetabulum causing pain and loss of movement (Wytch et al, 1989). Using the design of the Thompson prosthesis, the McKee-Farrar arthroplasty was developed in 1951, with a metal cemented acetabulum to prevent this problem. This arthroplasty produced excellent immediate results but with time, loosening of the components occurred. Design modifications were undertaken and 1965 had the first cementless cup design was introduced.

Simultaneously in 1964 Ring and colleagues developed an uncemented metal on metal (Chrome-cobalt-alloy) prosthesis using the ideas from the Moore prosthesis (Centerpulse Orthopaedics, 2002). But Charnley, with his low friction arthroplasty had the first positive longer term results with good outcomes at follow up (Charnley, 1972). The Charnley arthroplasty relied on the small stainless steel femoral head on the high-density polyethylene cup to reduce friction and the wear effect on the components. This design reduced the incidence of loosening and returned the patients to pain free movement (Charnley, 1972).

From 1960-70's several other hip arthroplasties were designed with the Stanmore prosthesis (Duff-Barclay et al, 1966) being the most competitive to the Charnley. The difference between the two designs was the size of the head of the femur. In 1963, the Stanmore design allowed the use of a variety of sizes of femoral head depending on anatomical structure, initially with a metal acetabular cup (Scales & Wilson, 1969) but in 1970 a high-density polyethylene cup was introduced. This design had a collar around the neck of the femoral component, which was thought to dissipate the weightbearing forces through the remaining bone tissue around the shaft of the prosthesis to lower the loosening rate. The success rate was once again good with relief from pain and increased mobility (Wilson & Scales, 1973).

Since the success of these designs many others have been developed however the longer term survival rates are still better for the Charnley and the Stanmore prosthesis (NICE, 2000). Ongoing changes in design related to fixation of the prosthetic components and modifications to enhance prosthetic longevity for younger patients continue to be sought to decrease the complications of loosening or wear and friction.

The most important alternative to cementing the prosthesis in place is bio-ingrowth or osteointegration: a natural growth of bone around or through the prosthetic implant. No cement is used and attachment is achieved by new bone growth at the bone/ prosthetic interface. Bone growth is enhanced by the tightness of the 'press fit' of the component, where the resulting trauma and compression to the bone stimulates new growth (Royal College of Surgeons, 2000; Rothman & Hozack, 1988). The surface of the 'press-fit' prosthetic component is often coated with beads (e.g. PCA total hip replacement), mesh or gouged with holes or grooves as a threaded self tapping bond to allow attachment of the new bone (Royal College of Surgeons, 2000; Wytch et al, 1989). Additionally a coating of hydroxi-apitate on the prosthetic component may stimulate bone growth (Royal College of Surgeons, 2002).

The use of a totally cementless technique in 'younger' patients (under 65 years) undergoing arthroplasty has been reviewed and results indicate that many have to be revised at a later date (NICE, 2000; Fitzpatrick et al, 1998). Recently cementing only one component of a total joint replacement (hybrid system) has gained favour (Zimmerman et al, 2002). If loosening occurs, an uncemented joint can be revised to a cemented joint (Rothman & Hozack, 1988).

Since the 1990s the use of modular components where different sizes of femoral heads made from differing materials to the same femoral stem has been instigated. The re-use of metal on metal prosthesis along with polyethylene acetabular liners within metal shells, or ceramic heads often with a hybrid fixation system may be used (Royal College of Surgeons, 2000; Callaghan et al, 2000) to reduce wear in the management of younger people with OA of the hip (Zimmerman et al, 2002). This is

Table 2.1 Revision rates for THR (Fitzpatrick et al, 1998)

Prosthesis	Number of studies (follow up time: years)	General revision rate (%)(range)
Charnley	52 (11)	4.7 (0–18)
McKee-Farrar	6 (10)	13.2 (4–23)
Stanmore	5 (11)	7.3 (6-22)
Charnley-Müller	5 (11)	15.5 (3-45)
Lubinus	5 (8.8)	3.2 (0-17)

particularly important in younger more active patients where wear of the components is accelerated (Paling, 2003). However for the older patient who make up the majority of those getting THR surgery, the prosthesis of choice remains the metal on polyethylene with cement fixation. In the UK, results would indicate that either the Charnley, Stanmore or Exeter prosthesis have the best outcome with up to 20-year survivorship (NICE, 2000; Gerritsma-Bleeker et al, 2000; Fender et al, 1999; Fitzpatrick et al, 1998; Britton et al, 1996; Marston et al, 1996; Murray et al, 1995).

Surgical techniques for THR have also seen improvement with advances in both the soft tissue management (Charles et al, 2004; Longjohn & Dorr, 1998) and the use of minimally invasive surgery (MIS) (Siddiqui et al, 2005). The use of MIS has been around for over a decade using anterior incisions but it is only in the last 7 years that MIS has been undertaken through a posterior approach. There are no long term results for this type of surgery or on the survivorship of the prosthesis. Studies do show that the length of stay in hospital, pain level and rehabilitation time may be significantly reduced due to: limited soft tissue damage, less blood loss and early mobility post operatively (Siddiqui et al, 2005). Many studies to date have "hand picked" their patients for surgery so hence the advantageous results may be a reflection of this. Until a large long term random control study has been undertaken then the results of MIS cannot be compared with that of traditional surgical techniques.

2.2.2 Prosthetic survivorship

There were 64 hip prostheses available to the UK health market in 2003 and many of these do not have any evidence of effectiveness (NAO, 2003). The most researched prosthetic designs are the Exeter, Charnley, McKee-Farrar, and Stanmore prostheses (Faulkner et al, 1998). In a meta-analysis of the outcomes and cost effectiveness of THR with different prosthesis Fitzpatrick et al (1998) found that the Charnley prosthesis was the most highly published along with the McKee-Farrar, Stanmore and Charnley-Müller arthroplasties which had been monitored for up to 10 years. Extensive data (15,707 hips) was also available for the Lubinus prosthesis but this prosthesis is only available in Scandinavia (Fitzpatrick et al, 1998). Revision rates for these prostheses are highlighted in Table 2.1.

The survivorship rates appear to be longer for cemented prosthesis compared to uncemented (Faulkner et al, 1998; University of Leeds, NHS Centre for Reviews and Dissemination, 1996), but cemented designs have been around the longest. Longer-term results for the newer uncemented techniques are not yet available, but the medium-term results (10 years) were very similar for both cemented and non-cemented porous-coated prostheses (Faulkner et al, 1998; Hozack et al, 1993). NICE (2000) recommend that the benchmark in the selection of prostheses for primary THR is a survival rate of $\geq$90% at 10 years for a successful outcome.

The current designs of the Charnley and Stanmore prostheses have survivorship data for up to 25 years. (Keener et al, 2003; Gerritsma-Bleeker et al, 2000; Older & Buterack, 1992; Alsema et al, 1994). In general, the revision rate at 5-10 years would be 4% (Marston et al, 1996) with more senior or experienced surgeons having lower revision rates (Marston et al, 1996; University of Leeds, NHS Centre for Reviews and Dissemination, 1996). Gerritsma-Bleeker et al (2000) report a prosthetic survival rate of 85% at a mean of 22 years after surgery with a population with an average age of 85.7 years. Twenty-one patients (22 hips) were assessed and only one of the 20 Stanmore hips with the original prosthesis had signs of a loose acetabulum, but 40% had indications of wear.

In a larger study at 15 years after surgery Britton et al (1996) found that the Charnley prosthesis had a poorer survival rate than the Stanmore. It was noted that the later Stanmore models with the new cementing technique, had a better survival rate at 10 years than the earlier models (97% compared to 92%). As most of the Charnley prostheses were undertaken prior to the Stanmore, different and earlier cementing techniques could explain why they did not have such good survival rates. This assumption is in agreement with the findings of the review of effectiveness of primary THR (Faulkner et al, 1998) where newer or 'second generation' cementing techniques were found to give better survivorship rates. Fender et al (1999) support these findings for the Charnley hip prosthesis with a revision rate of 9% being found in 1080 hips at 5 years after surgery. This rate is higher than that reported by others (e.g. Older & Buterack, 1992) but may be more representative, as a much larger survey population was used. In one of the first studies of survivorship in younger patients Keener et al (2003) reported a 31% revision rate in Charnley arthroplasties in patients receiving their surgery under the age of 55 years, when they were followed up at 25 years post-operation.

The main reasons for revision were found to be aseptic loosening (2.3%), deep infection (1.4%) general loosening (5.2%) (Fender et al, 1999), with increase in pain level being the main symptom for revision (Britton et al, 1997). From the Swedish hip register Herberts & Malchau (2000) found that 71% of revision was because of aseptic loosening but that the number of revisions in Sweden had decreased to 3% at 10 years mainly due to advances in the surgical technique. Schmalzried et al (2000) found that joint use, male gender, height, weight and hip joint centre of rotation were highly correlated with wear of the prosthetic components.

Leg length discrepancies after total hip replacement have been cited as a possible cause of post-operative hip problems (Williamson & Reckling, 1978). The expected leg length differences between operated and non-, is less than 2 cm (Brand & Yack, 1996). Woo and Morrey (1982) found a mean lengthening on the operated side of 1cm. when assessing 333 THR patients, whilst Williamson & Reckling (1978) studied 121 subjects with primary THR and reported a mean lengthening of 1.6±0.95cm. on the operated side.

Brand & Yack (1996) showed that the normal disparity of 2cm does not significantly influence the forces across the hip joint and is therefore not likely to cause long term problems to the hip replacement. Alterations of 3-6 cm, however normally increase the forces across the hip on the short side by between 2-12%, whilst on the long side the force reduced by 6%, but should remain with in normal limits. The moments across the hip joint on either the "short" or the "long" leg did not change significantly. This paper does not project what would happen in the long term with these altered forces acting on the hip joint and whether this will influence survivorship.

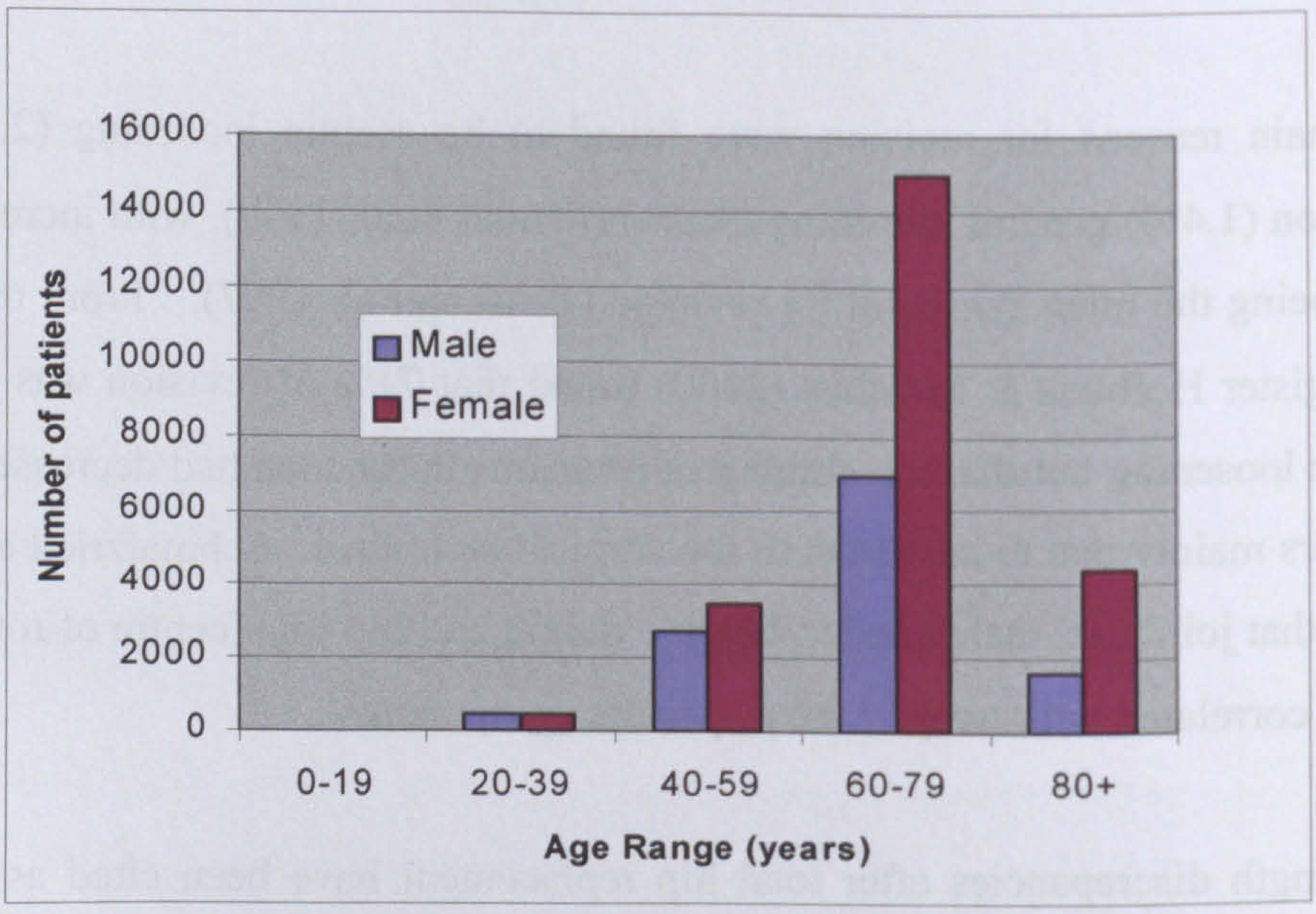


Figure 2.2: Age and Gender of Hip replacement patients 1998 - 1999, (NAO, 2000)

The review paper on leg length discrepancy (LLD) by Gurney (2002) highlights that there is a difference of opinion in whether LLD is related to back pain and balance problems. However Gurney presents data which shows that a real limb discrepancy in later life is more difficult to cope with and may lead to significant back pain or gait / balance problems, where this may not be the case in earlier years. In patients with OA hip, Gofton & Trueman (1971) found that of the 67 patients they assessed 36 had a limb length discrepancy, with 29 of these having arthritic changes on the long side. It is suggested that the long limb discrepancy may be a causative factor in OA.

White & Dougall (2002) recorded leg lengths in 200 patients six months post THR showing no correlation between leg length discrepancy and patient satisfaction.

2.2.3 Current issues in Total Hip Replacements (THR)

2.2.3.1 Numbers of THRs undertaken in UK

Current figures indicate that on average 43,000 THRs are carried out in the NHS in England and Wales each year (NAO, 2003) with a further 3,304 hip replacements being undertaken in Scotland in 2001 (Health Technology Board Scotland, 2002). This does not account for the unpublished numbers being undertaken in the private health sector.

The number of THRs is increasing on a year by year basis from 38,000 England and Wales in 1999 (NAO, 2000; NICE, 2000) to a total of 43,000 in 2002 (NAO, 2003) as a direct result of increased longevity (ARC, 2003). The upper age limit for THR is also being extended to 90-95 years and occasionally 100 (NAO, 2003, page 21), with as good outcomes of surgery as in younger people (Pettine et al, 1991). However the lower age limit is also reducing with people less than 55 years of age now having THR surgery (Fear et al, 1997; Mallory, 1992). Of the total number of THRs performed, women outnumber men by nearly two to one and the over 65-year age group accounts for two in every three (NAO, 2000) (Figure 2.2). Recent research relating successful post operative outcome to pre-operative functional state (Katz 2006; Fortin et al, 1999; Foucher et al, 1998) may encourage patients to demand earlier intervention and hence cause an increase in the number of joint replacements.

2.2.3.2 Costs

The total THR cost to the NHS was more than £140 million in 1999 (NAO, 2000) but increased to £184 million in 2002 (calculated from numbers in NAO, 2003) due to both the rise in the cost of the operation and the numbers being undertaken.

In 2002, the average cost of a primary hip replacement was £4,274 rising from £3,899 in 2000, with a range of £2,266 to £7,456. The average cost of a revision hip replacement in 2002 was £5,756, with a range of £2,260 to £11,489 (NAO, 2003). The cost of the prosthesis ranges from £250 - £2000 (Murray et al, 1995a). The NHS has to meet this increased expenditure, and there are now a number of agencies involved in the hip replacement service who are investigating means of reducing the overall costs of surgery while maintaining quality of service (See Appendix A).

The National Audit Office, 2002 survey, identifies the main ways of reducing costs as:

1. Reducing purchasing costs of prosthesis,
2. Reducing number of revision procedures,
3. Reducing length of hospital stay,
4. Introducing integrative care pathways to streamline the admission and rehabilitation processes,
5. Supplying more patient information and,
6. Undertaking more continuous clinical audit on hip replacement outcomes.

(NAO, 2003)

Part of the costs of THR is the post operative rehabilitation including physiotherapy. The physiotherapist is involved in the care of the patient with a THR at a number of points in the care pathway from pre-surgical treatment to the end stage of rehabilitation and follow-up (Chadda, 2000). From the list above change to physiotherapy services could impact primarily on items 3, 4, 5, 6 above and secondarily on item 2.

2.2.3.3 Reducing length of hospital stay

In the last few years the length of NHS hospital stay for primary hip replacements has decreased from 11 to 8 days and for revision surgery from 16 to 11.5 days (NAO, 2003). These are now similar to the times in the private sector where the recommended average length of stay for a primary replacement is 6 days and 9 days for a revision. These recommendations are not fully adhered to as the range of hospital stay in BUPA hospitals for primary THR shows variability, increasing from 7.9 days for those aged 40-49, to 12.7 days for those over 80. (BUPA, 2002). The Orthopaedic Services Collaborative recommends that for patients with primary THR without complications length of stay should be 5 days (NAO, 2003). Although the general trend is towards this goal, realistically the length of stay will be variable and is dictated by age, complications, and home circumstances.

In the National Audit Office (NAO), 2003 survey, nearly 60 per cent of consultants indicated that length of hospital stay could be reduced further by up to 3.5 days mainly through:

- earlier access to rehabilitation and physiotherapy services;
- improved discharge planning, and
- improved patient education. (NAO, 2003)

There is minimal published evidence on the extent or value of physiotherapy services at the early stages of rehabilitation (Heaton et al, 2000) further investigations would need to be undertaken (Chadda, 2000). The major consequence of reducing length of hospital stay would be the opportunity to treat more patients, with a consequent reduction in rehabilitation whilst in hospital. There is a general consensus that reduction in length of stay of as little as one day per patient in a 40 bedded unit could allow a minimum of 146 more patients to be treated with a THR. It is projected that a 3 day saving per patient could lead to 612 extra patients being treated (NAO, 2003).

Although the reduction in length of stay in hospital may reduce the costs in the acute sector, there may be significant implications for the general management of the patient and the services needed to gain full recovery. The implications on physiotherapy services are considerable.

Thomas (2003) reports the effect of introducing a clinical care pathway on the management of people with hip and knee arthroplasties. Indicating that up to five days was saved on length of hospital stay by introducing a twice-daily physiotherapy program during hospital stay and daily at home treatment for two weeks after discharge. Attendance at outpatient physiotherapy was also recommended after the initial two-week discharge period with ongoing review at six, 12 and 24 weeks. Although the costs for reduced hospital stay were calculated, the costs for time and resources for inpatient, outreach and outpatient nursing and therapy services have not been given. Unfortunately the Thomas paper does not compare the costs of the clinical pathway introduction to those prior to its use. Examination of the effect of reduced hospital stay and the patient's return of hip movement, muscle power or function in either the short or long term, still needs to be undertaken.

2.2.4 Outcome measures

The most effective means of monitoring the success of total hip replacements has been through the evaluation of outcome measures (NAO, 2000). There are numerous outcome measures to assess THR depending on the question being asked or the persons undertaking the assessment. Seventy five per cent of consultants follow up all their hip replacements, with 15% following up complex cases only and the other 10% undertaking not to do any follow up. Most consultants who follow up patients do so two or three times in the first post-op year, only 24% follow up for the lifetime of the patient, with 11% reviewing every year and 13% every five years. Interestingly the British Orthopaedic Association: 'Best Practice Guidelines' on total hip replacement indicates that most surgeons discharge their patients at 1 year (BOA, 1999). Thirty-four per cent of consultants do not follow-up patients after the first year (NAO, 2000). Of those who follow up their patients fewer than half of consultants measured patient outcomes of hip replacement surgery, and of those that do, fewer than half do so on a continuing basis. The NAO state: "*We consider that the lack of comprehensive outcome information on hip replacements is a matter of concern.*" (NAO, 2000, page 36).

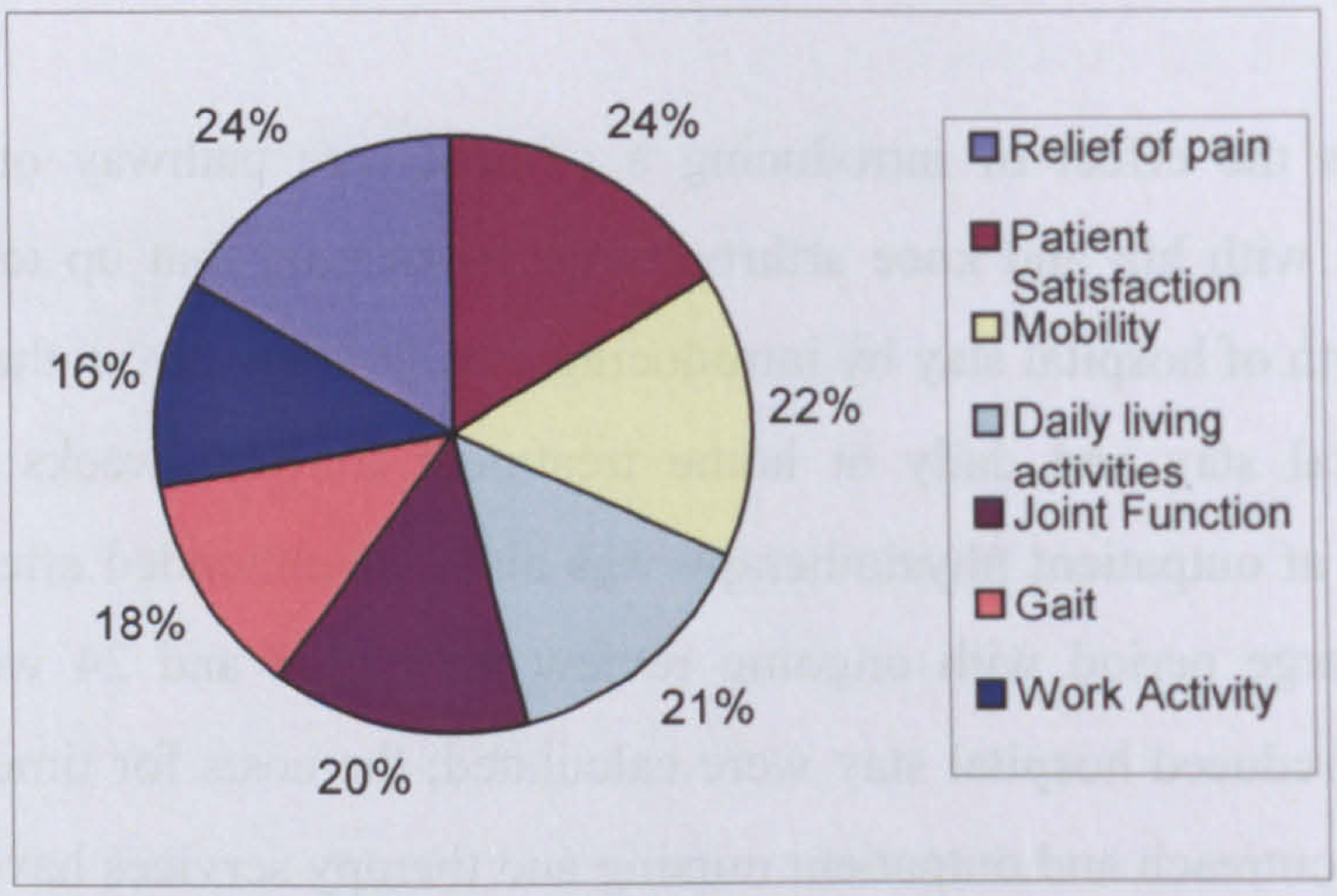


Figure 2.3 Number of consultants (expressed as %) using continuous clinical audit to evaluate outcomes of hip replacement surgery (NAO, 2000)

There is also a marked difference in what is included in the assessment (Figure 2.3), (NAO, 2000) with pain levels and patient satisfaction appearing to be the most commonly assessed outcome being undertaken by only 24% of consultants surveyed. From the extensive number of papers published on the outcomes of THR surgery most of the earlier publications appear to be a review of the longevity of the prosthesis rather than functional outcome. It is only in the last 10 years that the outcomes have widened to include the categories below:

1. Pain level (Britton et al, 1997),
2. General outcome rating scores which include a number of subsections: e.g. Harris Hip Score (Kili et al, 2003; Söderman & Malchau, 2001), Oxford Hip Score (Hajat et al, 2002; McMurray et al, 1999), & Quality of life Scores (Ethgen et al, 2004)
3. Functional scales: gait, activities of daily living (Fear et al, 1997),
4. Patient satisfaction (Heaton et al, 2000; Espehaug et al, 1998), & experiences (Montin et al, 2002)
5. Surgical outcome: medical surgical complications, length of stay in hospital, re-admission or revision rates, costs, radiographs etc (Zimmerman et al, 2002),
6. Impairment measures: Muscle strength (Shih et al, 1994) Physiological Movement (Thomas, 2003), Sashika et al, 1996)
7. Biomechanical analysis (Syczewska et al, 1998, 1999; Loizeau et al, 1995; Thurston & Harris, 1983).

The range of tools available to assess these categories is extensive, a few of these will be discussed in this section together with their reliability results. Gait and movement analysis will be reviewed later in section 4.4.

2.2.4.1 Pain

In all the published data on the consequence of THR, pain reduction is quoted as being extremely good and is the main successful outcome of surgery (NAO 2003), with patients with the non-cemented techniques having more pain than their cemented counterparts (Zimmerman et al, 2002).

In the majority of studies reviewed, the subjective graded visual analogue scale (VAS) was used to assess THR pain. The scale requires the patient to draw a mark on a 10-cm horizontal or vertical line with the end points of no pain and unbearable pain, to indicate their pain level (Duncan et al, 1989). From the vast array of measures of pain available, either physiological or behavioural, a visual analogue scale has been shown to give a good representation of either pain intensity or pain relief (Chapman et al, 1985). Jensen et al (1986) compared the VAS with five other scalar or categorical measures: the 101 point numerical rating scale, 11-point box scale, a six point behavioural rating scale, the four point verbal rating scale and the five point rating scale. Using the criterion of ease of administration and scoring, 75 people with chronic pain did not rate the VAS highly but, in the ability to judge acute pain levels, the VAS scored highly (Jensen et al, 1986). Therefore although the VAS was regarded as being very good at judging the level of the pain, it may be complicated to administer or understand.

The VAS is particularly suited to the clinical environment because it is quick and easy to administer (Waterfield & Sim, 1996; Jensen et al, 1986). The graded linear VAS (as described above) has been shown to be the most useful type and to be more reliable and preferable to descriptive or categorical pain scales (Chapman et al, 1985). The disadvantage of the VAS is that it is entirely individual and the level of pain indicated by one person may have totally different meaning for another and it is difficult to use with people with cognitive or sight problems. Equally it only gives a narrow view of the multi-faceted problem of pain (Waterfield & Sim, 1996).

Pain duration and intensity are the main predictors of both needing a THR (Birrell et al, 2003) and failure of the THR once inserted (Britton et al, 1997). Zimmerman et al (2002) report a steady increase in pain reduction from 57% at two months after surgery in 249 THR patients, to 63.5% at one year in 245 patients using a self reported pain scale. A significant change ($p<0.0001$) in pain score was noted in 62 OA patients before and after (3, 6, 12 months) hip replacement with the greatest change occurring in the first three months post-operation (Borstlap et al, 1994).

Similarly patients with RA (n = 35) also had a significant change in pain ($p<0.01$) but this was much more gradual over the 12 month period.

The results of MacWilliam et al (1996) are very similar to those of Borstlap, with the maximum change in pain score at 0-3 months post-operation. MacWilliam et al also noted that 16% of people had no significant change in pain level in this time period and that no significant change in pain occurred between 6-12 months. However maintenance of pain reduction beyond one year after THR has been shown to occur (Woolson et al, 1985; Kirwan et al, 1994.) There is no researched evidence why this should occur but positive adaptation to the THR may have occurred after one year post surgery.

To investigate the clinical benefits of THR surgery on back pain Ben-Galim et al (2006) studied 25 patients following THR for severe OA and reported significant reductions in pain scores (Visual analogue scale: $p<0.01$ hip and $p=0.013$ lumbar spine) and functional outcome scores (Harris Hip score ($p<0.01$) and Oswestry Spinal Disability score ($p=0.02$)) following THR surgery. They suggest that the reduction in spinal VAS scores and increase in functional scores is a direct result of the THR surgery, however there is no comparison to a control group and therefore it is unknown if the group scores returned to "normal" levels. These are the first researchers to investigate back pain changes following THR surgery.

2.2.4.2 General Outcome Scores and Quality of Life

General outcome scores combine either self reported or independent measured results from a number of different areas i.e. pain level, hip movement, activity level, quality of life etc. There are two main scales used in the UK to assess the general function of the hip joint either pre or post THR.

The Harris Hip Score (HHS) is widely used to assess hip function (e.g. Kili et al, 2003; Söderman & Malchau, 2001; Pettine et al, 1991). It was designed by Harris, 1969 to report levels of pain, function, deformity, range of motion and walking ability, by giving an overall numerical value to hip function. Rowe et al (1989) report the use of the Harris hip score to assess post-operative recovery following THR. The score is influenced by the degree of pain and therefore post-operatively the results change dramatically once pain has been relieved: mean HHS 50 at operation, rising to approximately 85 at six months and 92 at 12 months. The score therefore is not as appropriate for use after 6 months following surgery.

The other commonly used scale is the Oxford Hip score, which again uses sections on hip pain and disability to get an overall numerical value for hip function (Hajat et al, 2002). The score generated (12-60) indicate the level of symptoms with the higher scores indicating greater problems. There is no evidence on whether this scale is more sensitive to change 6 months after THR.

There are a number of general scales used in the literature, which are not hip specific. In the USA and Scandinavia the Western Ontario McMaster's Osteoarthrosis Index (WOMAC) is often used to give a self-administered indication of disability (Nilsdottir & Lohmander, 2002; Söderman et al, 2001b) this scale is disease specific. An alternative score used in the UK is the Nottingham Health Profile (NHP) which is widely used to give an indication of general health (Franzen et al, 1997). Outcomes from the NHP and HHS scores have been found to be comparable (Garellick et al, 1998b), so linking specific hip scores to a general health scale. Likewise the Medical outcomes Study 36-Item Short Form Health Survey (SF-36) is a general scale but very widely used for all populations (Nilsdotter & Lohmander, 2002). Ethgen et al (2004) in their systematic review of health related quality of life in joint replacement showed that of the 58 studies that looked at THR the predominant tool was the SF-36 or the WOMAC. Scores were the same as those for a normal age and gender adjusted population, at 6-12 months after THR.

In a large study of 2604 THR patients, Söderman et al (2001a) found good correlation (r_s =0.56 – 0.58) between SF-36, NHP, the WOMAC and the HHS (r_s 0.56-0.78), and suggested that all of these forms could be used to assess the outcome following THR as all related well to clinical outcome. However the pain scale in the HHS was the best indicator of clinical outcome when assessed against clinical and X-

Table 2.2 Number of treatments and post-operative days to achieve independent function. (Zavadak et al, 1995).

Task	Number of Treatment sessions Mean (SD)	Number of post-op. days Mean (SD)
Sit to stand	5.5 (3.3)	4.7(2.4)
Supine to sit	7.2(3.6)	5.8(2.6)
Walking 100 feet	8.1(2.8)	6.2(1.8)
Climbing stairs	9.5(2.6)	6.9(1.4)

ray failure (Söderman et al, 2001b). Söderman et al (2001a) recommended that for completeness, a general health form and specific hip scale form be used together.

2.2.4.3 Functional Measures

In many publications, surgeons have designed their own functional scales to measure problems with activities of daily living, specific functions or gait (e.g. Dorr et al, 1997) and comparisons across studies are limited. The main function to be assessed after a THR is gait, this will be discussed separately in section 4.4 and 4.5.

Zavadak et al (1995) assessed the early return of functional milestones after THR, looking at supine to stand transfer, sit to stand transfer, walking 100 feet, climbing stairs, all basic mobility requirements. A scale of functional ability was used where the number of days to attain completion of the task independently, with the use of walking aids as required, and the number of physiotherapy sessions to achieve this were recorded. As expected the results for walking and climbing stairs took the longest time to be achieved and supine to sitting was slightly more difficult than sit to stand for patients after THR (Table 2.2). This type of scale is very gross with the only category of success being 'independent movement'. The classification is very arbitrary, recording only attainment of the task with no regard to the quality of the movement.

The four point categorical scale: (no assistance, equipment, human assistance, and did not perform the task) used in the Physical activities of daily living score (PADL) (Zimmerman et al, 2002) gives slightly more information on attainment only but not quality of movement. The Harris Hip Score (HHS) is often used to assess functional ability in people with hip problems specifically (Kili et al, 2003; Norman-Taylor et al, 1996; Borstlap et al, 1994). The HHS has two function categories: gait and activities (see Appendix B). This gives more detail than the other scales with a degree of quality as the scale reports if the patient limps and needs support to walk.

Using a self rating scale which measures ability to walk, limp, ability to dress and other function related questions MacWilliam et al (1996) found that 76% of THR patients showed improvement in their physical function at six months post-operation. The results at 12 months were very similar to those at six with only a non-significant small rise in the numbers of people reporting increased mobility. It is interesting that 24% of people did not show significant change in functional ability in the first six months and that this situation did not change up to 12 months. No published research has looked at similar functional achievement at longer than 12 months.

Morlock et al (2001) used a portable monitoring system to assess the percentage activity (standing, silting, lying, walking, stair climbing) in 31 patients 3-360 months after THR. They found that frequency of activity was sitting (44.3%), standing (24.5%), walking (5.8%), lying (5.8%), and stair climbing (0.4%). This novel way of assessing functional recovery may be helpful for reviewing THR recovery but needs further exploration. Similarly Goldsmith et al (2001) assessed activity levels using a pedometer and found that patients post THR (58.4 yrs, mean follow up 14.2 years post op) walked slightly more than their healthy counterparts.

2.2.4.4 Patient satisfaction & experiences

Patient satisfaction in all aspects of the surgery has been reported extensively over recent years but this is less prevalent for the rehabilitation process. In the NAO (2000) report of THR, it was reported that 33% of health care trusts in the UK measure patient satisfaction annually, 38% less frequently and 20% not at all. In the same report only 24% of consultants assessed patient satisfaction on a continuous basis (NAO, 2000). The results form patient satisfaction surveys have been used to advance patient information, clinical environment, and introduce changes in practice that have improved patient quality of care. Few reports, however, look at the therapy services and the patients' views of these services.

A qualitative study (Heaton et al, 2000) on 58 patients, 26 relatives and 27 professionals looked at the effectiveness of rehabilitation for THR investigating in particular the extent to which patients' goals were achieved at four months post-operation. Semi-structured interviews were conducted before and after THR surgery *"to determine patient expectations of and satisfaction with their rehabilitation"* (Heaton et al, 2000). The Oxford hip score was also used to assess if the patient was satisfied with their surgical outcome. The majority of patients were satisfied that their expectations had been met at four months post-operation but 16% assessed their surgery to be only partially successful. It is unsurprising to note that the patients with multiple problems or developed problems after surgery were those who fell into this group (Heaton et al, 2000). In a questionnaire study of patient satisfaction, Espehaug et al (1998) showed that 84% of patients following primary THR reported that their satisfaction with the surgery/ implant was either good or very good, however no definition of "good" or "very good" was reported in this article.

In a recent qualitative study Montin et al (2002) report patient experiences from focussed interviews on 19 patients at 4 days and 8-12 weeks after THR. The main experiences identified from content analysis were on physical, psychological and social aspects. Pain, rest and mobility were the main physical experiences before surgery and these were retained to some degree after. One of the strongest experiences was tiredness post surgery and the belief that they had become debilitated by the wait for surgery. Patients also felt difficulty with the movement restraints post operation but did not have any issues with the extent or quality of the movement as this was better than pre-surgery. Patient satisfaction allows assessment of whether the patient is generally happy with the process or procedure but again does not give specific detail of the quality of movement.

2.2.4.5 Surgical outcome

The assessment of surgical outcome is mainly of use to the orthopaedic medical team as it includes issues of medical surgical complications with X-Ray indication of loosening, fracture, wear etc., length of stay in hospital, re-admission or revision rates, range of joint movement, or costs. Historically these variables have been most commonly used to assess 'good outcome' after surgery (Wilson & Scales, 1973; Charnley, 1972), in particular the researchers would review the longevity of the prosthesis (Fitzpatrick et al, 1998). Recently this information is gathered along with a more functional performance data (Zimmerman et al, 2002). This thesis does not specifically investigate surgical outcome.

2.2.4.6 Impairment measures

There is limited published data on impairments after total hip replacement with most work containing a small number of participants within a short post operative time scale. Muscle strength has been assessed between surgical approaches (Minns et al, 1993) or after early stage post operative exercise routines. Shih et al (1994) assessed pre and post (six and twelve months) muscle strength of the hip flexors, extensors and abductors in 20 men and 20 women (age range 24-71 years). Muscle recovery continued until at least one year post operation with the women showing biggest changes. Sashika et al (1996) reported significant changes in muscle strength in participants at 6-24 months post surgery (n=16, age 63.3±8.9yrs) when they followed a strengthening regime rather than concentrating on hip mobility. Longer term hip abductor muscle strength reduction is also reported for 15 patients from 9 months to 6 years after hip replacement (Sicard-Rosenbaum et al, 2002).

Gilbey et al (2003) assessed both functional scale and impairment measures in 37 patients at 3, 12, 24 weeks post surgery (age 66.73±10.19) and it is this combination which appears to give the best overview of general patient ability after hip replacement, however this does not necessarily give full information of the state of the joint and possible mechanical alterations.. Long et al (1993) showed that force plate data recorded at one year post surgery in 18 patients with non-cemented THR showed hip weakness without any observable change in clinical signs.

2.2.4.7 Biomechanical Analysis

Biomechanics or 'the application of mechanical laws to living structures' has been used to establish many of the facts on normal and pathological hip movement and function including that after THR. There is a considerable amount of published work in all aspects of biomechanics: kinematics, kinetics, muscle activity or energy expenditure which has evaluated patient and prosthetic performance pre and post total hip replacement.

3.0 LITERATURE REVIEW: Part 2

HIP AND LUMBAR SPINE ANATOMY

The background to OA and THR has been reviewed with the general outcome measures in the management of THR. This chapter looks specifically at hip and lumbar spine movement and their role in functional tasks in those with normal and pathological motion. Before reviewing these, an outline of the hip and lumbar spine will be given.

3.1 HIP JOINT

The hip joint is a multi-axial diarthrodial ball and socket joint with three degrees of freedom. The main function of the joint is to carry the weight of the head, arms and trunk in both static and dynamic activities and to transmit forces between the pelvis and the lower limb (Norkin & Levangie, 1992). The joint works efficiently in the weight-bearing, extended position, when the lower limb is stabilised on the pelvis (Hamill & Knutzen, 2003). The best articular contact between the acetabulum and the head of the femur is in a position of flexion, abduction and slight lateral rotation, loose packed position, (Norkin & Levangie, 1992) and it is suggested that this is the true physiological position of the joint (Kapandji, 1989).

The main physiological movements are: Sagittal plane - Flexion & Extension,
Frontal plane - Abduction & Adduction, Horizontal plane - Medial & Lateral rotation.

The hip joint is one of the most stable joints in the body due to the rigidity of the ball and socket, the strong ligament structure surrounding the joint and the large muscles on the lateral and posterior aspects (Nordin & Frankel, 2001). Despite its stability, the hip joint has a large range of movement and combines with the pelvis and lumbar spine to afford almost 180° of movement in the sagittal plane. The centre of the hip joint lies approximately 1.2cm inferior to the middle third of the inguinal ligament (Williams et al, 1989).

3.1.1 Anatomy

The hip joint consists of the head of the femur, which articulates with the acetabulum of the pelvic girdle.

3.1.1.1 Pelvis and Acetabulum

Each side of the pelvic girdle consists of three bones: ilium (superior), ischium (posteroinferior) and pubis (anteroinferior) connecting anteriorly by the pubic symphasis. Posteriorly the ilium connects with the sacrum at the sacroiliac joints (SI), synovial joints with strong ligaments to anterior and posterior surfaces. The SI joints also represent the junction of the spine to the lower extremity, transmitting the trunk load to the hip joint and vice versa. The SI joint acts as the energy absorber for shear forces during walking (Hamill & Knutzen, 2003). The acetabulum sits at the inferior lateral aspect of the pelvis facing obliquely forward, downward and outward and is marginally smaller than the head of the femur (Kapandji, 1989), marking the fibrous connection of the three pelvic bones. A thin layer of horseshoe shaped articular cartilage, thicker at the superior margin and absent inferiorly and centrally covers the inner third of the acetabulum and the transverse acetabular ligament (Nordin & Frankel, 2001) and accommodate the major weightbearing loads (Williams et al, 1989). The acetabular labrum encircles the acetabulum deepening it and providing a more stable socket. The labrum deforms to the shape of the head of the femur giving it extra stability on weightbearing and protects the main loading areas at the superior, anterior-superior and posterior-superior aspects of the hip (Nordin & Frankel, 2001).

3.1.1.2 Femoral head and neck

The spheroid shaped head of the femur (HoF) is approximately two thirds of a sphere with the neck protruding to hold the shaft of the femur away from the hip joint, and is smaller in women than men (Norkin & Levangie, 1992). Articular cartilage covers the HoF totally, except for the attachment of the Ligamentum Teres. The cartilage is thicker at the central area and thinner at the periphery, in opposition to that of the acetabulum, accommodate maximal load bearing and gives stability (Williams et al, 1989). The neck of the femur consists of cancellous trabecular bone surrounded by thin cortical bone, giving strength, particularly on the inferior aspects where the maximal load is exerted on weightbearing (Hamill & Knutzen, 2003). The cancellous bone is reinforced at the inferior femoral neck into medial and lateral trabecular systems (Oatis, 1990b), with the path of the ground reaction force of weightbearing mirroring the medial trabecular formation, emphasising the importance of this organisation (Kapandji, 1989). A further trabeculae structure fans out from the internal shaft of the femur to the greater trochanter giving more lateral strength (Oatis, 1990b). The neck of the femur is strengthened at the most vulnerable points to allow transfer of weight-bearing forces and because of the effect of muscle tension. With age the bone structure of the femoral neck changes, with loss of cancellous bone and gradual absorption of the trabeculae thus the femoral neck is prone to fracture (Nordin & Frankel, 2001).

In the transverse plane the neck of the femur lies at an angle of approximately 125° (range 90-135°) to the shaft of the femur (the angle of inclination) in the mature adult. The angle is generally smaller in women because of the greater width of the pelvis (Norkin & Levangie, 1992). The angle of inclination decreases with maturity, decreasing further in old age (65 yrs+) to 120° (Norkin & Levangie, 1992). With age there are altered stresses on the hip joint because of the reduction in angle of inclination, with resultant hip abductor muscle force and loss of femoral bone structure (Hamill & Knutzen, 2003). This potentially leads to secondary force changes and abuse of the articular cartilage. The angle of inclination of the femoral prosthesis needs to emulate that of the mean (125°) for best results (Noble et al, 1988), although Charles et al, 2004 reported that Charnley (1979) suggests that the most appropriate shaft angle to be 135° to gain the best mechanical advantage for the hip abductors and resultantly less force across the hip joint and less prosthetic wear. Charnley's suggestions have been supported by laboratory evidence from Davey et al (1993).

In the frontal plane, the angle of anteversion (angle of torsion) is approximately 12° with a change in the angle causing a greater range of rotation. With increased medial rotation, as per OA of the hip joint, alternative weightbearing surfaces are subjected to load and these may not have sufficient cartilage cover to survive the large forces of weightbearing. The femoral prosthesis in THR needs to be inserted at the correct angle of torsion to bear weight efficiently.

3.1.1.3 Capsule and ligaments

A thick strong capsule surrounds the hip joint, attaching 0.5 cm above the acetabular labrum, to the outer surface, descending in a sleeve like structure encapsulating the femoral neck. Distally the capsule attaches to the trochanteric line of the neck of the femur anteriorly and the base of the neck posteriorly above the line between the greater and lesser trochanters (Kapandji, 1989). The capsule is thicker and stronger in the anterior and superior areas (Norkin & Levangie, 1992), to help stabilise the hip joint, with the stronger posterior muscles (Williams et al, 1989).

The short triangular Ligamentum Teres passes into the acetabular foramen to attach to the fovea on the HoF to help supply its main blood and nerve supply. Although this ligament does not help to strengthen the capsule it is surrounded by a synovial sheath and becomes tight in adduction and flexion (Williams et al, 1989). The ischiofemoral ligament supports the capsule on the posterior aspect of the hip whilst the iliofemoral strengthens the anterior side with the pubofemoral ligament which also buttresses the medial component (Norkin & Levangie, 1992; Hamill & Knutzen, 2003).

The superficial longitudinal capsular fibres are stretched on sagittal plane movement with the iliofemoral and pubofemoral ligaments tight in full extension pulling the joint surface together to give more stability. Although the ischiofemoral ligament lies posteriorly, its circular fibres become taut in extension. The deeper circular capsular fibres form a collar around the femoral neck (Zona Obicularis) and tighten on rotation but all will contribute to preventing extension (Norkin & Levangie, 1992).

As a result of the configuration of the capsule and ligaments distraction of the hip joint is minimal but is more likely to occur in flexion and abduction. Dislocation of the hip joint is much more likely to do so in the anterior or inferior direction.

3.1.2 Kinematics of the normal hip and pelvis

The hip moves by the head of the femur rotating in the acetabulum when the lower limb is non weight-bearing but in the weight-bearing situation the reverse occurs where the acetabula/ pelvis rotate on the head of femur during trunk flexion and extension (Williams et al, 1989). Therefore hip movement cannot be looked at without considering movement of the pelvis. The next section addresses pelvic movement, then hip movement and finally how these interact.

3.1.2.1 Pelvic movement

As the pelvis is a continuous ring of bone, minimal movement of the individual bones is only possible at the three fibrous joints and this is highly controversial (Levin et al, 1998; Jacob & Kissling, 1995). When movement occurs, it is mainly en mass with the whole of the pelvis moving together. The pelvis, however, is the attachment site for 28 muscles of the thigh and trunk with none of them acting solely on the pelvic girdle so the main role of the pelvis is not as a prime mover.

Movement of one lower extremity with consequent movement of one side of the pelvis will influence the function of the other limb (Hamill & Knutzen, 2003). Pelvic movement is described by the position of the anterior inferior and superior iliac spines (AIIS, ASIS). In the non-weight bearing position, anterior tilt is the forward and downward motion of the ASIS in the sagittal plane around the Frontal axis, this can also be called lumbo-pelvic rhythm. Anterior tilt occurs when the thigh or trunk extends. When the thigh or the trunk flexes, posterior tilt of the pelvis takes place and the ASIS & AIIS move up and backwards. In the weight-bearing position, anterior tilt represents flexion at the hip and posterior tilt represents extension (Norkin & Levangie, 1992). With the hip in the flexed non-weight-bearing position, there is a greater capacity for tilt in either the posterior or anterior direction. In standing, supine or prone the hip is in extension and this limits the degree of tilt possible (Hamill & Knutzen, 2003).

Lateral pelvic hitch (drop) predominantly occurs in single limb stance in the frontal plane. The ASIS of the pelvis normally lie horizontal in the frontal plane but they can be raised in lateral pelvic hitch or drop, resulting in a raised or lowered ASIS when viewed from in front. With one limb unsupported, the ASIS on the non-weight-bearing side drops unless the hip abductors (Gluteus Medius) on the weight bearing side contract concentrically to prevent it. Some degree of lateral pelvic tilt will occur with lateral movement of the trunk or abd/ adduction of the thigh but this is minimal.

Lastly, the pelvis will rotate en mass either forwards or backwards to either the right or left side on unilateral thigh movements. When the right thigh moves forward (flexion), the pelvis rotates forward to the opposite side (left) and vice versa. In contrast when the left thigh moves backwards (extension), the pelvis rotates backwards to the right. When forward rotation of the pelvis occurs, there is a concurrent medial rotation of the supporting hip joint and lateral rotation of the hip will occur with posterior pelvis rotation (Norkin & Levangie, 1992).

3.1.2.2 Hip movement

Hip joint movement is much easier to understand and as mentioned previously this occurs in all three planes around three axes:

- Sagittal plane, Transverse axis - Flexion & Extension
- Frontal plane, Anteroposterior axis - Abduction & Adduction
- Horizontal plane, Vertical axis -Medial & Lateral rotation

Passive hip range of movement is nearly always greater than active and the maximal recognised and accepted values for normal adult hip (Hamill & Knutzen, 2003; Kapandji, 1989) are represented in Table 3.1 (p36A). James & Parker (1989) have undertaken a study of active and passive joint movement in healthy 70 – 90 year olds which has not been repeated to date (Table 3.2, p36A).

Table 3.1 Active and passive range of movement in the adult hip joint (Hamill & Knutzen, 2003; Kapandji, 1989)

Hip Movement	Plane	Active	Passive
Flexion (knee flexed)	Sagittal	120- 135°	145°
Extension (knee flexed)	Sagittal	10°	30°
Flexion (knee extended)	Sagittal	90°	140°+
Extension (knee extended)	Sagittal	20°	20-30°
Abduction	Frontal	30-45°	30-45°
Adduction	Frontal	30°	30°
Medial Rotation (knee flexed, sitting)	Transverse	30°	30°
Lateral Rotation (knee flexed, sitting)	Transverse	60 - 70°	70°+
Medial Rotation (knee extended)	Transverse	70°	70°
Lateral Rotation (knee extended)	Transverse	90°	90°

Table 3.2 Active and passive range of movement in the adult (70 – 74 years) hip joint (James and Parker, 1989)

Hip Movement (°)	Plane	Active (°)		Passive (°)	
		Males	Females	Males	Females
Flexion (knee flexed)	Sagittal	100	110	105	115
Flexion (knee extended)	Sagittal	67	74	70	80
Abduction	Frontal	32.5	30	34.5	33.5
Medial Rotation (knee flexed, sitting)	Transverse	30	29	34	34.5
Lateral Rotation (knee flexed, sitting)	Transverse	30	28.5	34	35

Knee joint position also affects the degree of movement possible in the sagittal plane due to stretch on the biarticular muscle of the Quadriceps group: Rectus Femoris, and the Hamstrings group: Biceps Femoris, Semitendinosus, and Semimembrinosus. With the knee extended, hip flexion is reduced by approximately 30° due to tightening of Hamstrings across the posterior aspect of the hip and knee. Likewise with the knee flexed hip extension is reduced as the Rectus Femoris is fully stretched across the anterior aspect of the hip and knee.

Hip rotation is also compromised by body position. The most commonly used position for testing hip rotation is prone lying with the knee flexed to 90° but as a result the Rectus Femoris is stretched limiting lateral rotation compared to measurement in sitting. Measurement of rotation in sitting is not as reliable as in prone lying (Kapandji, 1989). An alternative position to assess hip rotation is either in supine lying or standing with the hip and knee in extension. Sitting yields maximum hip rotation but as hip movement is combined with some knee rotation it gives a false value and is highly variable (Kapandji, 1989).

The average movement in the frontal plane is very dependent on pelvic position. If the pelvis and lumbar spine are controlled in supine lying the range of abduction and adduction will be as in Table 3.1 but if lateral flexion of the pelvis and lumbar spine occurs then the abduction can reached 90° and adduction 60°. Abduction is stopped by the neck of the femur contacting the rim of the acetabulum, whilst the lateral soft tissue halts adduction.

As a result of the large degree of movement available and the ball and socket configuration the hip joint is also capable of circumduction. Kapandji (1989) describes circumduction as "*the combination of the elementary movements occurring simultaneously around the three axes*" (Kapandji, 1989, page 14). The ranges given above are for adult hip movements but the issues of age and gender need to be explored.

3.1.2.3 Age and gender influence on hip movement

Hip movement through the decades from 70 years shows a gradual diminishing of range particularly for the male population for both active and passive movement (James & Parker, 1989). Hip abduction was shown to have the greatest change over the decades decreasing by 33% from 70 – 74 years to 85+ years but the largest change took place between the end of the 8th and 9th decades ($p<0.01$). This pattern also emerged for hip medial and lateral rotation with the decrease in hip flexion occurring between 80- 84 years to 85+ years.

The main difference between the range of hip movement in males and females is the significant reduction ($p<0.001$) in range of active and passive hip flexion with knee extension or flexion in males (James & Parker, 1989). Women have shorter absolute hamstrings length than men do but when adjusted for femur length this is not significant (Gajdosik et al, 1990). Muscle length alone cannot account for reduced hip flexion with knee extension in men. It is known that men have tighter biarticulate muscles than women mainly due to the larger muscle mass and this may reduce hamstrings length extensibility (Gajdosik, 1991). It is hypothesised that this is the cause of the reduced hamstring length in men (Gajdosik et al, 1990).

Roach & Miles (1991) reported active hip range of movement in 1,683 healthy people aged 20-74 years and found that their results differed from the anatomy books by a mean of 18° when measured with a Universal goniometer. Measuring three age groups (25-39, 40-59, 60-74 years), the movement was lowest in the oldest age group. The average change with age was 3-5° in each of the hip joint movements except for hip extension but variability was high with the three groups overlapping considerably. On average there was a 20% reduction in hip extension as age increased to 74 years, indicating that the expected range would be 8-15°. Total hip rotation does decrease with age in women, especially on the left hip with lateral rotation decreasing significantly on both sides but only the left side showed a highly significant reduction in medial rotation (Hall et al, 1987). This study only measured women up to 59 years and it is not known if this pattern of change continues through the age where hip pathology would become more evident or indeed is responsible for hip problems.

There is limited data on passive range of movement but recently Nonaka et al (2002) assessed hip and knee flexion and extension in 77 healthy males between the ages of 15-74 years of age in three age groups (teens, forties, seventies). Measurements were taken, via photographic analysis, with the knee extended and flexed so investigating the effect of the biarticular muscles. Using a geometrical representation these authors demonstrated that maximal passive movement reduced with age at the hip but not at the knee, with a significant correlation between age and hip flexion and extension, $r = -0.49$, $p<0.001$ and $r = 0.58$, $p<0.001$, respectively. It was calculated that the age related change in passive movement was -0.17° for flexion and 0.27° for extension per year. Likewise the length of hamstrings and quadriceps also reduced with age at a reduction of -0.25° and 0.36° per year, the authors predicted that this is due to a decrease in activity level over time (Nonaka et al, 2002). There has not been an equivalent study of females so it can only be assumed that a similar pattern would be seen.

The schematic analysis undertaken in the study by Nonaka et al, 2002, has also been used with children with cerebral palsy and been shown to be highly effective in visually displaying change in movement scores (Kuno et al, 1998).

3.1.3 Physiological movement of the Osteoarthritic hip and THR

Physiological movement is defined as the range of passive and active movement of a joint. As a result of any hip pathology the hip joint reverts to the tight capsular position of flexion, adduction and lateral rotation, resulting in loss of hip extension, abduction and medial rotation.

There is limited published literature on the hip kinematics in those with hip OA, however it is believed that there are significant differences in hip physiological range of movement between a hip with OA and those without. Thurston (1985) in the study of spinal and pelvic movement in patients with OA reported that hip range of

Table 3.3 Outcome for hip arthroplasty (Thomas, 2003), Mean (SD)

Function	Pre admission	Discharge	6 weeks	3 months	6 months
			After surgery		
Flexion (°)	75 (18)	60(16)	77(13)	82(11)	83(11)
Abduction (°)	16(10)	17(9)	28(8)	31(10)	34(8)
Extension (°)	-3(9)	-5(8)	4(11)	8(10)	10(10)
Time to walk 10 m (s)	12(11)	33(20)	13(11)	9(4)	8(3)
Walking aid (%)					
None	41	0	32	62	70
Stick	44	0	30	32	30
Crutches	7	55	20	3	0
Frame	8	45	18	3	0

Table 3.4 Mean range of motion after hip replacement (Woolson et al, 1985)

Time of Visit	Flexion (°)	Abduction (°)	Adduction (°)	Medial Rotation (°)	Lateral Rotation (°)
Preoperatively	67.1	10.9	10.9	0.4	13.2
6 months	82.9	17	12.8	1.4	15.0
12 months	91.1	18.6	14.4	2.0	16.0
24 months	91.5	19	15.4	4.9	18.5
Mean 7.5 yrs	93.6	20.7	20.1	21.6	28.0

NB No Standard deviations were given in article.

movement on the side with OA was significantly ($p<0.001$) less than the side without but the author does not give details of how these measurements were taken or even if they are static or dynamic movements. Thurston also indicated that the movement on the non-affected side of the patients had a similar range of motion to the relative side on the control group.

In the most up to date research publication, Thomas (2003) reviewed 89 patients at admission and discharge and followed up 69 patients at six weeks, 65 at three and 56 at six months after THR surgery. The results of hip range of motion, walking aid used and time taken to walk 10 meters are presented in Table 3.3.

Pre operatively the mean data on hip motion indicated that the hip was held in fixed flexion but not fixed adduction, but there was a significant loss of all movements measured when compared to the normal values. Measurements were taken using a universal goniometer following the guidelines of Norkin & White (1995). The mean time to walk 10 metres was 12 seconds (±11) giving an average walking speed of 1.2m/s, which is relatively fast given the pathology involved. As 41% of the patients did not require a walking aid prior to surgery this, and the other variables, may suggest that these patients did not have major functional loss prior to surgery. There is gradual improvement of hip flexion, abduction and extension movement from discharge to three months after surgery, with the movement surpassing the pre operative range but does not reach the normal values for hip motion. Walking speed improved mainly between discharge and 6 weeks after operation with some continuing improvement at three months. Between 3-6 months there was no real change in walking speed or hip movement. There was however a continuing change in the type of walking aid required through to 6 months with 70% of people not requiring any walking aid and all the others only requiring a walking stick.

Similarly Woolson et al (1985) followed 108 hips in 92 patients for up to a mean of 7.5 years measuring their range preoperatively and at six, 12 and 24 months after operation (Table 3.4). There is no information on how the measurements were taken,

Table 3.5 Range of motion after hip replacement: Murray et al, 1975; Trudelle-Jackson et al, 2002.

<table>
<tr><th></th><th colspan="3">Degrees of motion (°)</th></tr>
<tr><th>Murray et al (1975)</th><th>Pre op</th><th>6 months</th><th>24 months</th></tr>
<tr><td>Flexion</td><td>90</td><td>105</td><td>109</td></tr>
<tr><td>Extension</td><td>-30</td><td>-23</td><td>-25</td></tr>
<tr><td>Abduction</td><td>6</td><td>12</td><td>16</td></tr>
<tr><td>Adduction</td><td>11</td><td>12</td><td>12</td></tr>
<tr><td>Medial Rotation</td><td>4</td><td>15</td><td>15</td></tr>
<tr><td>Lateral Rotation</td><td>16</td><td>18</td><td>20</td></tr>
<tr><th>Trudelle-Jackson et al (2002)</th><th colspan="2">12 months post THR</th><th>Matched Controls</th></tr>
<tr><td>Flexion</td><td colspan="2">93.7±18.7</td><td>95.9±16.0</td></tr>
<tr><td>Extension</td><td colspan="2">5.0±10.4</td><td>5.0±9.4</td></tr>
<tr><td>Abduction</td><td colspan="2">23.9±5.8</td><td>24.0±8.1</td></tr>
<tr><td>Adduction</td><td colspan="2">18.0±16.1</td><td>19.0±5.3</td></tr>
<tr><td>Medial Rotation</td><td colspan="2">24.1±7.8</td><td>24.5±7.8</td></tr>
<tr><td>Lateral Rotation</td><td colspan="2">21.2±5.1</td><td>22.5±6.7</td></tr>
</table>

except that a goniometer was used, extension was not measured and that no measures were taken of the non-operated limb.

Significant increases in range were made in adduction and rotation between the two-year period and the final follow-up. This was also the case from six to 12 months, but there was no significant change between one and two years post- operation. This may indicate that range on motion at one year can be used to predict range at two years. The range of hip rotation is very small at two years post-operation but increases extensively through to final follow-up from 4.9° to 21.6° for medial rotation and from 18.5° to 28° for lateral. Again as the measurement technique is not known it is difficult to compare results. These results are similar to those of Murray et al (1975) who assessed 83 patients at 2 years post THR finding significant loss of hip extension, where contractures increased between one and two years (Table 3.5). Interestingly neither hip abductor nor adductor strength had reached the lower borders of "normal" at two years. Trudelle-Jackson et al (2002) reported similar results to Woolson et al (1985) (Table 3.5) except that the degree of rotation was much greater for both medial and lateral rotation at the 12 month post-op stage.

When comparing data trends from Thomas (2003) and Woolson et al (1985) the range of motion at six months is very similar except for hip abduction, with the Thomas study identifying a much greater range. The results for Woolson and Trudelle-Jackson are similar at 12 months with Trudelle-Jackson showing a greater range of movement. Although direct comparison cannot be made between the results from all three studies as the precise measurement techniques for the Woolson results have not been reported it would appear that the Woolson results measure lower than either of the other authors. With no change in hip movement between 1 to 2 years (Woolson et al, 1985) it is surprising to note significant change to adduction and rotation at the 7.5 year follow up.

Sashika et al (1996) reported increases in hip flexion in a small randomised study of eight patients with THR following a six week general hip exercise programme; at 26.5 months post THR (range 6–48 months). No measurement information was given in this paper and as the numbers of participants is small, with very large standard deviations over a broad spectrum of post operative time, the results cannot be used for comparison of range of motion.

3.2 LUMBAR SPINE

The structure and function of the lumbar spine has evolved to perform its main functions: giving attachment to the muscles of the pelvic girdle and providing anchorage for these powerful muscles to move the vertebral column for balance and posture (Bogduk, 1997). The lumbar spine also surrounds and protects the spinal cord against injury, acts as a shock absorber via the normal curvatures and the intervertebral discs. Because of its strength and flexibility, the lumbar spine is able to produce and accumulate moments of force as well as to concentrate and transmit forces received from other parts of the body (Oliver & Middleditch, 1991).

The primary physiological movements of the lumbar spine and its individual joints are flexion, extension, lateral flexion, and axial rotation (Bogduk and Twomey, 1991). Axial compression, axial distraction, lateral and anterior-posterior shift all occur as accessory movements or in combination to complement the physiological movements (White and Panjabi, 1978).

In general forward flexion of the trunk occurs primarily at the lumbar vertebrae which produce the first 60°, then forward tilt of the pelvis completes the final 20° of forward flexion (Norkin & Levangie, 1992). Trunk extension occurs through the reverse movement in which the pelvis tilts posteriorly first, the lumbar spine continues the extension (approx. 35°) (Kapandji, 1990), and then the thoracic and cervical spines to gain a total range of approximately 60° (Bogduk, 1997). The total range of lateral flexion of the trunk is around 75°, occurring at the cervical (35°), thoracic region (20°) and lumbar region (20°) (Kapandji, 1990). During lateral flexion, there is a slight lateral shift of the vertebrae, with disc compression to the side of bend.

Total trunk rotation completes a 90° arc with most of the motion occurring in the cervical and thoracic regions (Kapandji, 1990). In the lumbar region rotation only occurs in combination with lateral flexion (i.e. right rotation accompanying left lateral flexion), thus pure rotation is limited in the lumbar region (5°) (White and Panjabi, 1978). Using X-ray analysis Pearcy et al (1984) studied three-dimensional lumbar spine motion, in six healthy male (mean 34.7 yrs (range 23-45) who performed flexion, extension, left and right twist, and left and right bend. Among those subjects they found consistent patterns of movement. There was always more flexion than extension with little or no accompanying twisting or bending, whilst twisting of the lumbar spine was always accompanied by a few degrees of vertebral flexion and lateral bend to the opposite side. Vertebral extension and rotation to the opposite side generally accompanied lumbar spine lateral bending.

Similarly Buchalter et al (1988) investigated three-dimensional lumbar spine motion using 60 normal subjects (27 males and 33 females, mean 31.7±6.4 yrs) with the 3-Space Hybrid System. Their results agreed with Pearcy et al (1987), showing that motion in the sagittal plane was coupled with a small degree of motion in the frontal and horizontal planes, while lumbar spine lateral bending was accompanied with the opposite vertebral axial rotation.

Specific interactions of the pelvis and lumbar spine will be explored in section 3.2.3.

3.2.1 Anatomy

The basic anatomy of the lumbar spine is not disputed, so a short summary will be given here with notes taken from Bogduk (1997), Oliver & Middleditch (1991), Williams et al (1989), White & Panjabi (1976 & 1978). Details of stabilisation of the spine and the role of the soft tissue can be found in Panjabi (1992a,b)

3.2.1.1 Bones

The five vertebrae of the lumbar spine are the largest in the spinal column. They are numbered according to their position (L_{1-5}), with L1 being the most cephalad and are attached inferiorly to the five sacral and coccygeal vertebrae. Each vertebral segment comprises a body series and an arch series (Kapandji, 1990). The body series contains the vertebral body, which is approximately cylindrical in shape with its front and sides being concave from top to bottom for weightbearing, with the largest in the lumbar and sacral regions. The vertebral body cross sectional area is greater in males than in females, increasing with age by 25-30% in males but not in females (Mosekilde & Mosekilde, 1990).

The arch series starts from the vertebral bodies, as a pair of posteriolaterally running pedicles, which form a vertebral arch with a corresponding pair of laminae. The laminae slope backwards to meet in the midline to form the posterior projection of the spinous process. At the junction of the pedicles and the laminae arises a lateral projection, the transverse process with two articular surfaces.

In making contact with the inferior articulating surface from the vertebrae above the superior articulating surfaces form a small synovial zygapophyseal joint. These joints are typical synovial joints. Therefore for every two vertebral segments there are two zygapophyseal joints and it is the shape and contact of their articulating surfaces which designate the degree and type of movement which can be carried out at each vertebral segment. In the lumbar region the shape of the articular facets falls into 2 categories: flat or curved ('J' or 'C' shaped), and the angle of orientation either towards the frontal or sagittal plane. $L_{1/2}$, $L_{2/3}$ and $L_{3/4}$ are more often curved, $L_{4/5}$ almost equal numbers of flat and curved and L_5 /S_1 almost totally flat. The shape and orientation of the facets governs the control of rotation and forward slide of the vertebral bodies.

A large central foramina for the spinal cord (vertebral canal) is formed by the bony junction of the vertebral body and the pedicles/ laminae. It is said that the anterior convex curve or lordosis in the lumbar region develops from the posteriorly convex curves or kyphosis, of the thoracic and sacral regions (Williams et al, 1989). The values for these curvatures vary in the individual. There are only minimal curvatures in the sagittal plane (scoliosis) in the normal spine; reviewing a variety of literature Renshaw (1988) showed that 2-3% of the population have a lateral curvature of the spine of 10° or less which is normally in the thoracolumbar region.

3.2.1.2 Articulations of the Vertebral Column

The three articulations of the vertebral column are referred to as a motion segment and consist of the intervertebral discs which join the anterior portion of the vertebral bodies together, and the posterior portion. As previously mentioned they are united by the pair of zygapophyseal joints reinforced by the strong interspinous and intertransverse ligaments. The motion segments at the junctions between the spinal regions are subjected to the greatest stresses, in both the static and dynamic postures due to the alteration in postural alignment from lordosis to kyphosis and vice versa (White & Panjabi, 1976). This is particularly so in the relatively short lumbar spine where there are only five vertebrae joining with the sacrum at the L_5/S_1 motion segment with a very acute change from lordosis to kyphosis. Also at the cephalad end the T_{12} /L_1 junction changes less acutely from lordosis to kyphosis (Bogduk, 1997).

3.2.1.3 The Intervertebral Disc

The vertebral bodies of the lumbar spine are larger than those in the cervical and thoracic regions, thus the intervertebral discs are consequently bigger and increase in cross sectional area as the spinal level descends, offering a greater degree of flexion, extension and lateral bending (Bogduk, 1997). Conversely, the smaller the disc height, the smaller the available rotational movement.

The intervertebral discs consist of two parts; the soft hydrophilic centre named the nucleus pulposus, and the fibrocartilaginous lamellae outer layers of the annulus fibrosus. The nucleus lies slightly posterior in the lumbar spine due to the spinal posture at this level.

Hyaline cartilage end plates are found on each of the superior and inferior surfaces of the vertebral body indicating the anatomical boundaries of the intervertebral disc. The end plates protect the vertebral body from pressure atrophy, confine both the annulus fibrosus and nucleus pulposus within their anatomical boundaries and act as a membrane to facilitate fluid exchanges between the annulus, the nucleus and the vertebral body (Palastanga et al, 1989). The nucleus pulposus and annulus are not separate structures but consist of differing densities of collagen fibres. The nucleus pulposus has a three dimensional lattice of collagen in which is enmeshed a proteoglycan gel. The water content of the gel, is approximately 80-88% in adolescent life but reduces to 70% by the age of 50 years (Palastanga et al, 1989), reducing the overall height of the disc. During spinal motion, the nucleus acts hydrostatically to evenly distribute pressure therefore acts as a shock absorber.

The annulus fibrosus has numerous annular bands, consisting of obliquely running fibres of fibrocartilage, which are at greatest in number in the innermost bands. The anterior portion of the annulus contains a greater number of fibrocartilage fibres than the posterior. The posterior part often has irregular patterns of fibrocartilage which can become weaker with age or rotational stresses allowing damage to the disc and protrusion of the nucleus pulposus (Troup, 1986; Palastanga et al, 1989).

During weightbearing and daily activities, the disc is subject to compression, bending torsion (Nordin & Frankel, 2001) and shear (Radin et al, 1979). Flexion and extension and lateral flexion of the lumbar spine produce compressive and tensile stresses on the intervertebral disc and rotation produces shear stresses. In the lumbar spine the relative ratio of disc diameter to height is small limiting rotational movement. With age the available range of motion is also reduced because of the alteration in lumbar disc height, loss of elasticity, inability to store energy and reduction in the ability to distribute loads.

3.2.1.4 Ligaments

The ligaments are the high-tension bands of the vertebral column having a high collagen content whose relative inelasticity limits their movement during vertebral motion thus stabilising the spine. The main ligaments are formed in two groups, the anterior series contains two ligaments, whilst the posterior series has five (Williams et al, 1989).

The anterior and posterior longitudinal ligaments extend the whole length of the spine, spreading over the respective aspects of the sacrum to gain their lower attachment. Both are attached to and support the intervertebral disc but only the anterior longitudinal ligament is attached to the vertebral bodies. The posterior longitudinal ligament forms the anterior wall of the vertebral canal and cross sectional area and density are considerably smaller than the anterior ligament (Williams et al, 1989). The ligaments of the posterior series are shorter and are located between each motion segment supporting the zygapophyseal joints and the spinous and transverse processes.

3.2.1.5 Muscles

The muscles surrounding and supporting the vertebral column are many and complex, therefore only a brief outline of the muscles supporting the lumbar spine and their actions will be given. It should be noted that the muscles of the hip joint which attach to the pelvis, in particular the Gluteus Maximus, medius and minimus, Rectus Femoris and Quadratus Lumborum, all have a major role in stabilising the pelvis and thus the lumbar spine to allow the prime movers to work.

The muscles of the trunk and abdomen lie in three regions anterior, posterior and lateral. The function of these muscles depends not only on their anatomical position but also on the direction of the fibres, either longitudinal or transverse. The longitudinal muscles mainly control gross flexion/extension, e.g., Rectus Abdominus & Erector Spinae, and side flexion movements e.g., Quadratus Lumborum, of the thorax and lumbar spine. The short transverse muscles e.g., Multifidus, Semispinalis, Rotatores, control posture and stability (Williams et al, 1989). A proportion of the longitudinal muscles is inserted diagonally to control rotation e.g., External & Internal Obliques with all muscle groups combining to give support to the abdomen and assist respiration.

The short back muscles provide stability over the individual vertebral segments to allow the posterior muscles (especially erector spinae) to control gross movement. The interplay between the anterior, posterior and lateral trunk muscles allows very specific and controlled movement of the thoracic and lumbar spines.

3.2.1.6 Spinal Cord

The strong bony structure around the vertebral canal protects the spinal cord and vertebral vessels travelling within. The spinal nerves leave each segment of the cord via the intervertebral foramina, an arch formed by the pedicles of adjoining vertebrae.

Table 3.6 Ranges of segmental motion aged (25-36years) (n = 11)
(Pearcy et al, 1984, Pearcy & Tibrewal, 1984)

Mean range (Degrees (SD))							
	Lateral Flexion		Axial Rotation		Flexion	Extension	Flex & Ext.
Level	Left	Right	Left	Right			
L1-2	5	6	1	1	8(5)	5(2)	13(5)
L2-3	5	6	1	1	10(2)	3(2)	13(2)
L3-4	5	6	1	2	12(1)	1(1)	13(2)
L4-5	3	5	1	2	13(4)	2(1)	16(4)
L5-S1	0	2	1	0	9(6)	5(4)	14(5)

In total there are five pairs of spinal nerves in the Lumbar region. Each nerve is named after a related vertebrae and leave the canal at its corresponding intervertebral foramina, e.g. L_1, the first lumbar nerve root leaves the canal in the foramina formed by the L_1 and L_2 pedicles, with the L_5 nerve root leaving between the L_5 and S_1 pedicles etc. The spinal cord ends opposite the vertebral level of $L_{1\text{-}2}$ and from this point the spinal nerves travel down the vertebral canal to leave at their appropriate intervertebral foramina. Surrounding the spinal cord are two layers of sensitive soft tissue (dura) which allow friction free motion of the cord in the vertebral canal and are impregnated with the nerve and blood supply to the spinal cord and local tissue. The nerves in the dura have a randomised pathway extending along its length, which is particular to each individual. Therefore pressure or damage to the dura, at any level, may cause pain distribution through out the length of the spine (Troup, 1986).

3.2.2 Individual vertebrae movement

Pearcy et al (1984) studied three-dimensional X-ray analysis of normal static movement in the lumbar spine, using 11 males (29.5yrs (range 25-36)), showing that each intervertebral joint had a mean total range of flexion/ extension of approximately 14° (Table 3.6). Differences were seen in the pattern of movement at each level. $L_{1/2}$ producing slightly more flexion than extension, but $L_{2/3}$, $L_{3/4}$ and $L_{4/5}$ have greater flexion with decreased extension. $L_{3/4}$ and $L_{4/5}$ showed very little extension, with most of their movement being flexion. At the $L_{5/S1}$ level no discrete pattern was found but as per the $L_{1/2}$ segment extension was decreased slightly and flexion increased. The range of L_4/ L_5 movement was statistically greater than the levels above ($p<0.05$), but not for the movement at L_5/ S_1. The difference in the lower lumbar spine movement may partly explain the higher incidence of joint failure at this level (Bogduk, 1997).

Coupled motions of lateral bend and axial rotation were similar at each lumbar intervertebral level, varying from 0 to 2° (Pearcy & Tibrewal, 1984). The ranges of active rotation and lateral bending and the accompanying rotations in those planes were explored in 20 healthy subjects, using a three-dimensional radiographic technique.

Overall there was approximately 2° of axial rotation at each intervertebral joint, with $L_{3/4}$ and $L_{4/5}$ showing slightly more mobility. Eleven degrees of lateral flexion occurred at the upper three lumbar levels with the $L_{4/5}$ and $L_5/\ S_1$ demonstrating 8° and 2° respectively. Axial rotation to the right in the upper lumbar spine was accompanied by lateral bending to left and vice versa. In the $L_5/\ S_1$ joint, axial rotation accompanied lateral bending to the same side (i.e. right rotation with right lumbar lateral flexion and vice versa). Pearcy & Tibrewal (1984) did not show any consistent pattern of accompanying flexion or extension with either rotation or lateral flexion, with the mean sagittal accompanying movement being 0°. However the $L_{4/5}$ level had the largest accompanying flexion or extension movements of all lumbar joints. The intervertebral joints at the $L_{4/5}$ level experience the highest stresses and strains in comparison to the other levels, thus giving a mechanical reason for the $L_{4/5}$ levels to be the highest incidence of intervertebral pathology (Bogduk, 1997).

3.2.3 Lumbar spine, pelvis and hip interaction

One of the main functions of the lumbo-pelvic-hip complex is to provide locomotion, as well as to provide a stable base from which the upper body can operate (Lee, 1989). As movement of the hip, pelvis and lumbar spine are totally interconnected it is important to understand their interaction. The thigh can move independently of the pelvis and lumbar spine, but only through a limited degree of movement, however the pelvis and lumbar spine nearly always move together unless the trunk is stabilised i.e. supine or prone lying (Hamill & Knutzen, 2003). Thus to access pure hip or pelvis movement, supine and prone lying are excellent positions so long as the patient is comfortable (Hoppenfield, 1976). Movement of the lumbar spine and pelvis is termed lumbar-pelvic rhythm and was first used by Calliet. Levine and Whittle (1996) demonstrated a clear significant concomitant relationship between pelvic tilt and lumbar lordosis in 20 females mean age 23.4 (range 20-32)). Pelvic tilt and lumbar lordosis measures in normal standing posture were 11.3±4.3° and 31.8±7.3° respectively. Change to maximal anterior (11.4°) and posterior pelvic tilt (-8.7°) showed a resultant comparable change in lumbar lordosis angle 10.8°, anterior tilt and -9.0° posterior tilt, $p<0.001$ (Levine & Whittle, 1996). This change is not transferred to the thoracic spine according to Day et al (1984) when measuring 32 male participants in standing but their findings for the lumbar spine do concur with those of Levine & Whittle (1996).

The term lumbar-pelvic rhythm has been modified to show the three segments (lumbar spine, pelvis and hip) working together to produce a greater degree of movement (Norkin & Levangie, 1992). For example hip flexion with knee extension alone, would only reach a maximum of 90° but working with the pelvis and lumbar spine a person can reach the floor when bending forward a range of 130°+ (Norkin & Levangie, 1992). Likewise hip abduction alone can only reach 45° maximum but with pelvic hitch and lumbar lateral bend the leg can move through to 90°. The hip-pelvis-lumbar spine combination not only allows greater freedom of movement but also compensates when one of the segments is not able to function normally. This can be advantageous to general function but difficult if assessing true hip or lumbar spine movement, thus to ensure examination of individual joint movement, the compensation strategies have to be eliminated.

In forward flexion the pelvis tilts anteriorly and shifts backward and the reverse occurs during trunk extension with the pelvis tilting posteriorly and shifting forward (Oliver & Middleditch, 1991). The pelvis also moves with the lumbar spine during rotation and lateral flexion, however the movement relationship between the pelvis and the lumbar spine is not as clear as that in the sagittal plane because of the restrictions to the movement introduced by the lower extremity (Norkin & Levangie, 1992). Normally the pelvis will rotate with the lumbar spine e.g. right rotation of the pelvis with right lumbar spine rotation unless the lower extremity forces a rotation of the pelvis in the opposite direction. In this case the pelvis may remain in the neutral position or rotate to the side exerting the greatest force. Similarly, in lateral flexion of the lumbar spine, the pelvis will lower to the side of lateral flexion, unless there is resistance offered by the lower extremity (Lee, 1989).

Table 3.7 (p50A) gives an overview of the compensatory movements of the hip, pelvis and lumbar spine. If the hip is held in flexion due to OA or tight hip flexors

Table 3.7 Hip, pelvis and lumbar spine compensatory movement during right weight-bearing (Norkin & Levangie, 1992, p317)

Pelvic movement	Hip joint motion	Compensatory lumbar spine movement
Anterior Pelvic tilt	Flexion	Extension
Posterior pelvic tilt	Extension	Flexion
Lateral pelvic tilt (pelvic drop)	Right adduction	Right lateral flexion
Lateral pelvic tilt (pelvic hitch)	Right abduction	Left lateral flexion
Forward rotation	Right medial rotation	Rotation to left
Backward rotation	Right lateral rotation	Rotation to right

the pelvis will be anteriorly tilted and if not corrected the head, arms and trunk (HAT) will tend to be transferred forward. However the lumbar spine usually extends to maintain the HAT in the upright position allowing a better posture for easier function (Norkin & Levangie, 1992). These compensations allow any loss of hip movement to be masked, so that the common deformity of flexion, adduction and lateral rotation can be offset by lumbar spine; extension, lateral flexion and rotation with pelvic; anterior tilt, pelvic drop and backward rotation.

Investigating the relationship between hip and lumbar spine movement Lee and Wong (2002) assessed physiological movement in 20 males aged (20±1yrs) using the 3SPACE Fastrak. Having performed three maximal forward, backward and lateral flexion of the trunk, the degree of movement from each was correlated to movement at the hip. The ratios showed that hip and lumbar spine motion played an equal contribution to the overall movement of trunk flexion and extension, there was more lumbar spine movement at the start of flexion but then the hip took over towards the end of the motion. Lumbar lateral flexion was complemented by adduction of the hip to the side of bend and abduction of the opposite hip; however the main motion was from the trunk. Axial rotation of the trunk produced simultaneous lumbar spine rotation with medial rotation of the hip on the twisting side and lateral rotation of the opposite hip. Very little lumbar spine movement took place with the hips playing the major role.

This is the only study which has looked at this relationship and these will be useful for understanding the interaction of the hips and lumbar spine during function although the data were gained from only 20 young males. Similar results were found in a second study (Wong & Lee, 2004). These results, however, differ to those of Haideri et al (1997) who used the Vicon motion analysis system to assess spinal motion in 19 healthy adults (26 (range 14-36yrs). They showed that the pelvis (60°) was the main contributor to forward bend, followed by thoracic (40°) and then lumbar (30°) motion. Lateral bend occurred predominantly from the thoracic region (35°) with only minimal input from the lumbar (8°) and pelvic (6°) segments, whilst axial rotation was characterised by pelvic (56°) and thoracic (45°) motion with a small amount of lumbar movement (14°).

Caution needs to be taken when reviewing data on segmental interaction as different researchers define movement segments in different ways. As not all segments (hip, pelvis, lumbar spine etc.) are necessary measured then some reports do not give a full report of the motion, hence it can be difficult to compare data.

Hip, pelvis and lumbar spine interaction during specific functions will be reviewed in section 4.4.

3.2.4 Lumbar Spine Movement – Age and Gender

Using large populations, various researchers have shown that sagittal mobility of the lumbar spine is influenced by age (Griffin, et al., 1984; Fitzgerald, et al., 1983; Twomey, 1979) and gender (McGregor, et al., 1995; Griffin, et al., 1984; Troup, et al., 1968), although there is much controversy. There is no research evidence of physiological spinal motion in patients with OA except when undertaking walking. The results for this will be discussed in section 4.5.1, Lumbar spine motion during walking.

3.2.4.1 Age

Exploring three dimensional kinematics in the elderly lumbar spine using 12 older healthy subjects (seven females, mean 69 yrs and five male, mean 68.8yrs), McGill et al (1999) compared these results to a database of young people (Peach et al., 1998). The results indicated that the elderly group exhibited a significantly lower peak displacement value for full flexion (48° vs. 71°, $p<0.0001$) and lateral bend (left lateral bend 20° vs. 29°, right lateral bend 17° vs. 29°). Flexion motion in the elderly group was performed at a slower velocity than the younger group (38°/s vs 66°/s).

Peak velocities during lateral bending and axial twist movement were similar. The average velocities over the first 30° of movement and last 30° of movement were lower in both forward flexion and lateral flexion. No differences in peak acceleration were found during any movement task. Significant differences were found in the amount of the coupled motion during some of these movements. In flexion there was very little apparent coupling of motion in the lateral bend or twist axes, but during axial twist there was more apparent coupled motion with the flexion axes in the group of elderly.

Hindle et al (1990) investigated lumbar spine motion, using the electromagnetic 3-Space Isotrak device, in 80 healthy subjects (40 males and 40 females) in four age groups (20-29 yrs, 30-39 yrs, 40-49 yrs, >50 yrs). The general patterns of movements were shown to be remarkably similar in all age groups for both flexion and extension and no appreciable lateral bend or axial rotation was seen (mean values for all these measurements were close to zero). Lateral bend was accompanied by a significant degree of opposite axial rotation and flexion. Axial rotation was accompanied by lateral bend, but there was no consistent pattern of accompanying flexion or extension. Looking specifically at people over 50 years of age, males had greater range in all movements but particularly so for lateral flexion and rotation. These researchers only looked at a group of people between the ages of 50-57 years. Moll et al (1972a) indicated that increasing age results in a reduction of lateral lumbar spine mobility, which was shown to be more marked in females (35-38%) than in males (25-26%).

McGregor et al (1995) showed a gradual reduction with each decade ($p<0.001$) and that range of motion tended to be affected by age and sex, whereas velocity was affected only by distance moved. Maximum extension was the most severely affected by age, with significant difference between each decade. Flexion showed an initial reduction in motion after 30 years of age, then motion was maintained and a further reduction was seen after 50 years of age. There was no change in lateral flexion range between 20 to 29 age and 30 to 39 age groups, but after age of 40 years, significant reduction in range was seen at each decade. Range of right rotation was significantly reduced at each decade, while in left rotation no significant age effect was shown.

3.2.4.2 Gender

Using an inclinometer Loebl (1967) found that women have greater lumbar spine movement in comparison to men, but using the modified Schöber technique Macrae and Wright (1969) disagreed with these results, stating that men had greater flexion than women (7cm compared to 5.8cm). A later study by Moll and Wright (1971), also using the modified Schöber technique, explored the same relationship and also showed that men have marginally greater ROM in transverse axes (flexion-extension), while women had greater ranges of lateral flexion in comparison to men below the age of 75 years. Males showed lower degrees of flexion in their middle years, whereas females showed reduction in flexion in younger age and maintained that level through middle age, but had a further decline in movement at over 65 years of age. In extension, females retained their range up to middle age, whilst men showed a steady rate of decline. However the loss of extension in both sexes was proportionally less than that for flexion. In a more recent investigation of lumbar sagittal mobility, Burton and Tillotson (1988) used a flexicurve to measure 510 healthy subjects (242 males, 268 females) and their findings agreed with those from Moll and Wright (1971).

Overall, lumbar mobility was relatively well preserved in both sexes but a slight decline took place through middle age. In the group of the older males there was an increase in general spinal movement whilst an increase in extension only occurred in the older female group. Similar results were found by Troup et al (1968).

Hindle et al (1990) showed when measuring the mean lumbar range values for all ages (20-50+ years) that men have greater flexion (73.8° vs 66.7°), while women displayed more extension (24.1°vs 21.5°), lateral bend (54.1° vs 48.4°) and axial rotation (30.8° vs 27.1°). The statistically significant difference ($p<0.025$) between males and females was shown for flexion only. In the over 50 year old group Hindle et al showed that females had a larger degree of movement in all ranges with lateral flexion and rotation being significant. The work by McGregor, et al. (1995) found that when measured with the CA-6000 Spinal Motion Analyser the 60-70 year old group females had a significantly larger degree of flexion ($p<0.001$) and extension

Table 3.8 Summary of range of lumbar spine motion normal population aged 50 years and over

	Sex	**Flexion**	**Extension**	**LF (L)**	**LF (R)**	**Rot (L)**	**Rot (R)**
van Herp et al (2000) (°)	F	50.8(6.6)	15.1(5.2)	19.4(6.1)	19.2(5.6)	14.7(6.5)	13.0(6.0)
	M	52.3(8.2)	16.9(5.6)	14.4(4.6)	15.5(4.3)	10.9(3.9)	14.6(6.0)
McGregor et al (1995) (°)	F	54.6 (11.8) **46.6 (8.7)***	18.3(7.5) **15.6 (4.8)***	28.1(5.3) **25.4 (6.1)***	30.2(7.4) **26.4 (5.6)**	27.5(8.9) **25.4 (10.1)***	26.2(7.2) **23.4 (8.8)**
	M	60.2 (13.6) **45.0 (9.3)**	21.4 (6.8) **13.4 (7.3)**	31.5 (6.1) **27.0 (6.7)**	29.6 (6.1) **25.1 (7.7)**	27.0 (7.1) **23.6 (4.4)**	26.2 (5.9) **24.5 (5.1)**
Hindle et al (1990) (°)	F	73.0	21.1	50.5	50.5	29.3	29.3
	M	70.1	19.4	37.5	37.5	21.1	21.1
Moll and Wright (1971) (cm)	F	4.93 (0.90) **5.10 (1.07)**	2.72 (0.95) **2.63 (0.76)**	5.55 (2.16) **4.45 (2.07)**	5.56 (2.04) **4.45 (2.07)**		
	M	5.67 (1.31) **5.40 (1.26)**	3.41 (1.56) **2.40 (0.85)**	4.83 (0.98) **4.48 (1.49)**	4.44 (1.03) **4.50 (1.54)**		

Key: Mean data (SD): LF = Lateral Flexion, Rot = Rotation

van Herp et al (2000) participants aged over 60 years (3-Space Isotrak system)

McGregor et al (1995), participants aged between 50 to 59 years, participants **aged 60-70 years (data in bold)** (CA-6000 Spinal Motion Analyser). *significant difference between genders

Moll and Wright (1971), participants aged 65 to 74 years, participants **aged 75 years and over (data in bold),** (Tape measure)

Hindle et al (1990), **participants** aged 50 –57 years. (3-Space Isotrak system) (p<0.01) than males. Right lateral flexion and right rotation was also greater than males but this was not significant. Left lateral flexion and left rotation (p<0.01) were both significantly reduced in females compared to men. In the slightly younger group (50-59 years) McGregor et al showed that women had less flexion (54.6 vs 60.2°), extension (18.3 vs 21.4°) and left lateral flexion (28.1 vs 31.5°) and more right lateral flexion (30.2 vs 29.6°) than men, but there was no difference in either right or left rotation.

The results of Hindle et al and McGregor et al agree in general terms if not exactly; that men over 60 years of age have less movement in all planes. Although the results from these authors differ from the findings of Moll & Wright and Burton & Tillotson, the instruments used were more sophisticated and measured dynamic movement not static.

The main difference between the results of Hindle et al (1990) and McGregor et al (1995) is the type of instruments used and placement of these. The 3-Space Isotrak (Hindle et al, 1990) uses small light electromagnetic sensors, whilst the CA-6000 spinal motion analyser is a linked computerised triaxial potentiometric system (McGregor et al, 1995). The larger values attained by Hindle et al (1990) in a similar age group may be due to the lighter sensors allowing more movement. In terms of placement, McGregor et al (1995) placed the upper end of the spinal motion analyser at the thoracolumbar junction and the lower end at the level of the posterior superior iliac crests. Hindle et al (1990) however placed the sensors of the 3-Space Isotrak at the L_1 and L_4 levels. As the McGregor et al procedure encompassed more fixed vertebrae, T_{12} and $S_{1/2}$, the overall movement may have been more restricted.

When age was taken into account, female mobility fell proportionally more than that of males, with the exception of extension. Initial analysis of the results indicated gender and age differences in range of lumbar spine motion (Table 3.8). Generally research studies agree that a decrease in spinal ROM occurs in the ageing adults (van Herp et al, 2000; Troup, et al., 1968; Biering-Sorensen, 1984; Moll and Wright, 1971) and that there is a difference between lumbar spine mobility between males and females (McGregor, et al., 1995; Hindle, et al., 1990; Moll and Wright, 1971). Males are more flexible in the sagittal plane, while females are more flexible in frontal and transverse plane. From Table 3.8, it is clear that there are large differences between the ranges found by different authors e.g. van Herp et al (2000) and Hindle et al (1990) who used the same instrumentation as well as between measurement tools It is hypothesised that this is mainly due to the different populations used, tools used and the reliability and handling of the measurement instruments.

Table 4.1 Definitions of movement terms used in this text. Shumway Cook & Woolacott (1995), Carr & Shepherd (1990), unless stated specifically

Term	**Definition**
Kinetics	The measurement and analysis of forces, powers, and energies of movement e.g. ground reaction forces, joint reaction forces, moments of forces, tendon forces, joint contact force, power, work and energies (Winter, 1967).
Kinematics	The spatial movement of the body not including the forces that cause the movement e.g. linear and angular displacements, velocities, and accelerations (Winter, 1967).
Posture	The ability to maintain an appropriate relationship between body segment in stance or sitting which allows the body to be maintained in equilibrium with least expenditure of energy
Postural control	Regulating the body's position in space for the dual purposes of stability and orientation
Balance	A state of equilibrium or parity characterised by cancellation of all forces by equal opposing forces.
Movement	The act or instance of moving; a change in place or position
Function	The special, normal or proper physiologic activity of a part.
Compensatory strategies or compensation	Altered movement of body parts and angular displacements with altered muscle activation patterns to achieve a goal.
Motor Control	Study of the nature and cause of movement two main issues: Stabilising the body in space (postural and balance control) Moving the body in space (motor control in movement)
Recovery of function	Re-acquisition of movement skills lost through injury or disease

4.0 LITERATURE REVIEW: Part 3

MEASUREMENT, MOVEMENT AND FUNCTION

This chapter explores the issues of movement, measurement and movement during functional activity. Movement is the primary requirement of everyday life and the return to this is the paramount treatment outcome in physiotherapy.

> *"Clinical practices designed to treat the patient with motor dysfunction are based on an understanding of the nature and cause of normal movement, as well, as an understanding of the basis for abnormal movement. "* (Shumway Cook & Woolacott, 1995, p6)

Understanding measurement of movement is essential to offering effective treatment. Movement and function are inherently linked, as one cannot happen without the other. Human movement can be reviewed in six main areas: Physiological, Anatomical, Environmental, Sociological, Mechanical, Psychological (Trew & Everett, 2001). For quality and efficient movement the four main body systems: musculoskeletal, neurological, respiratory and cardiovascular, work together with psychological awareness to control body posture and alignment to maintain quality of movement and function. There are three essential components to the analysis of functional: measurement and data collection, presentation of the data and analysis of the data.

Movement terms used in the literature today are often confusing depending on the perspective taken and the definitions used. A list of the definitions used in this text is given opposite (Table 4.1).

In a summary paper on gait analysis methodology, Cappozzo (1984) highlights the complexity of gait analysis and distinguishes between gait analysis and evaluation. He identifies the least crucial stage of gait evaluation as the gathering of numbers to describe the mechanics of the patient's gait. It is not until the clinician is involved in the gait evaluation process that the synthesis of the multifaceted and complex data can be fully achieved. This section will deal with the instrumentation used to gather the data.

4.1 MEASUREMENT AND RELIABILITY OF HIP, PELVIS AND LUMBAR SPINE MOTION

Accurate measurement of three-dimensional kinematics is essential to the understanding of how normal human functions and to identify abnormal movement patterns. Reliability is the consistency to measure the same data on a repeated basis using the same instrument and technique or, alternatively, the consistency of measurement when all conditions are held constant (Rothstein, 1985). Either the same tester (intra-rater) or different testers (inter-rater) can be used, but for an instrument to be reliable then it should have both intra- and inter rater reliability. Parallel forms reliability is the comparison of two or more measurement devices to measure the same movement.

Payton (1988, p69) states that

> *"A reliable measurement tool is one in which the variance due to error is small in comparison to the variance due to real differences in the objects measured".*

Measurement tools also require construct validity tests i.e. what is being measured is true and defines what is being measured Payton (1988). This will be discussed later in the text.

To assist in understanding the research papers in the following sections the terminology and definitions of statistical analysis for reliability will be given.

4.1.1 Statistical Analysis for Reliability

There are various techniques for assessing the reliability of matched pairs of readings, but the main analysis used in this study were the Least Significant Difference (LSD) and Pearson's Product Moment Correlation Co-efficient (PPMCC).

Rose (1991) indicated that the LSD technique is more useful than other tests and is used when comparing measures of test retest or intra-rater reliability. To compare two sets of data from different tools measuring the same movement, or alternatively from two different people measuring the same thing with the same tool, Limits of Agreement (LOA) or PPMCC can be used. The PPMCC (r) measures the strength of the relationship between two variables, not the agreement between them (Bland and Altman, 1986). The value of LSD is the extent to which repeated measures must differ for this to be statistically significant, conversely, test/retest variations less than the value of LSD cannot be considered to be different (at the 5% significance level). The greater the LSD, the lower repeatability of the measurement and as LSD is expressed in units of clinical measurement it is particularly useful to clinicians. If the LSD for a particular measurement is known, it is possible to decide immediately whether the alteration in value of a clinical measurement is due to a change in mobility of the patient or merely to the lack of sensitivity of the clinical measurement used (Rose, 1991).

LSD uses the standard deviation (SD) of the test-retest differences and is calculated as: LSD = t * SD, where t is derived from two-tailed t-test tables, in this case the 5% significance level with degrees of freedom equal to the number of subjects minus one. For 10 subjects t = 2.262. Where the measured difference is below the level of the LSD there is insufficient evidence to conclude that underlying values are different (Tillotson and Burton, 1991).

PPMCC is based on the concept of covariance and calculates an index that reflects a quantitative measure of the relationship between two variables. The analysis from the PPMCC is called the r value and is given on a range of 0 to ± 1, with values nearer to +1 (perfect positive correlation) or -1 (perfect negative correlation) indicating the most reliable results. The magnitude of the correlation coefficient indicates the strength of the association between two variables. Portney & Watkins (1993) suggest that r values above 0.75 show a good to excellent relationship, 0.50 to 0.75 moderate to good, 0.25 to 0.50 fair and values 0.24 and below indicate little or no relationship. The r value should be given with the significance level indicating how likely it is that an observed correlation value would have occurred by chance. The significance of the correlation does not indicate the strength of the correlation, the r value does this. The size of the sample will have an effect on the statistical power with small sample sizes giving significant results at low r values: r=0.45.

$$r = \frac{n\sum XY - (\sum Y)(\sum X)}{\sqrt{[[n\sum X^2 - (\sum X)^2][n\sum Y^2 - (\sum Y)^2]]}}$$

The coefficient of determination (r^2) is the square of the correlation coefficient, and indicates the percentage of the total variance in one variable that can be explained by the other (Portney & Watkins, 1993). If the r value is 0.35, the r^2 value will be 0.1225, indicating that 12.25% of the variance in one variable can be accounted for by the other. This analysis is particularly of interest when the strength of the association of one variable to another is required.

The Limits of Agreement (LOA) give the upper and lower value for comparison of two sets of data from the same measurement, but using different tools or measurers. The upper and lower boundaries of LOA are calculated by the equation: mean of differences ($\bar{d}$) ± (t * SD of differences) (Tillotson & Burton, 1991). The range allows the researcher to assess if the values are clinically acceptable, the greater the range for the upper and lower values, the smaller the chance that the tools are interchangeable.

The alternative to the use of these statistical analyses is the Student t-test, Coefficient of Variation (CoV), or Intraclass Correlation Co-efficients (ICC). The t-test calculates the difference between the mean of two variables but does not identify the variability between the specific data.

The coefficient of variation (CoV) is a test of comparative variability and is calculated by: (sd/ mean)*100, the percentage of the variance around the mean. It has an advantage over the t-test as it expresses the standard deviation as a proportion of the mean, accounting for any difference in the magnitude of the mean. The index ranges from 0-100%, the lower the percentage the less the variance and the better reliability. Rothstein (1985) reports that CoV of <10% are acceptable in human measurement due to the variability of performance. The CoV is independent of units as it is a percentage, therefore can be used to compare differing unit values.

ICC give the most exact measure of reliability estimating the variance between each of two or more sets of data through analysis of variance. The ICC gives an index of reliability similar to that of the PPMCC. The ICC can be used when there are not the same number of raters per subject, and with either parametric or non-parametric data. To undertake this appropriately, however, at least 30 sets of data are needed.

The results in this study were calculated using the PPMCC(r) to assess the significant relationship between first and second measures so that comparisons can be made to the results in the literature. The least significant difference (LSD) was used to estimate the difference between matched pairs of readings at the 5% significance level (Bland and Altman, 1986) to give an analysis, which is appropriate in the clinical environment.

This section will now discuss measurement error before highlighting joint movement, measurement tools for use at the hip and lumbar spine, the reliability of these and will highlight specific problems.

4.1.2 Measurement Error

The potential sources of error in surface measurement are numerous. Some are from the choice of reference landmarks from which measurements are taken, intra-observer variations in technique, inter-observer variations in technique, a choice of measurement method and potential effects among the above (Nicol, 1989). Rothstein (1985) indicates that most joint measurement should be within a range of ± 5° to be reliable, giving an overall range of 10°. Measurement error is inherent in any tool and the more complex the tool the greater the error.

The common errors fall into these categories:

4.1.2.1 Soft tissue artefacts
4.1.2.2 Placement of the tool/ markers
4.1.2.3 Construct validity
4.1.2.4 Interpretation of data
4.1.2.5 Observer error: Intra and Inter-rater
4.1.2.6 Specific issues within the tool
4.1.2.7 Hip Joint Centre Location

4.1.2.1 Soft Tissue artefacts

Soft tissue artefacts (STA) accompany any measure where external markers are attached to the skin. Andriacchi & Alexander (2000) acknowledge STA as the major source of error in the analysis of human movement. Lundberg (1996) discusses the limitations of using skin markers instead of bone markers to reduce STA and suggests that there is limited knowledge in this area. He reports that STA error over the spine is less of a problem because the fascia over the spinous processes is quite rigid and therefore skin movement will replicate that of the underlying joints. Problems of measuring hip joint movement arise using both skin and bone markers because of the depth of the hip joint and because flexion and extension tend to have less error than other planar movements (Lundberg, 1996).

Thigh:

- Greater Trochanter moves mainly in the A/P direction 35 mm in 80°, 15 mm in M/L & Rot. The markers generally move forwards and up during flexion.
- The lateral epicondyle marker moves backwards during flexion with A/P movement of 25mm in 70° and Medial and Lateral and rotation movement of 10mm.

Shank

- A marker on the head of fibula moves back and down with knee flex., and forwards and upwards in ext. approximately 15mm in 70°
- Lateral Malleolus marker moves 10 mm in 60° of ankle movement, backwards with Plantar flexion.

There appears to be no relationship between skin movement and joint amplitude (Karlsson & Tranberg, 1999).

In recent studies Stagni and colleagues (2005, 2006) have looked at quantifying soft tissue artefacts (STA) through combination of 3D fluoroscopy and sterephotogrammetry and reducing the error through double calibration methods. In the 2005 study the STA was greatest in the thigh (up to 31mm) compared to the shank (up to 21mm) with the abd/adduction (PMS 192%) and medial/ lateral (RMS 117%) rotation angle being the most affected by the artefact during flexing the knee against gravity, rising from a chair and sitting down and step up and step down. The STA error for the proximal thigh showed the greatest STA with the error for the distal thigh showing the least.

The mean RMS values for knee rotations ranged from 2.6-9.2° for single calibration and 1.4-7.1° for double calibration, when two body postures were taken at the extremes of the range of movement for the activities highlighted above (Stagni et al, 2006). The linear knee translations for single and double calibration ranged from 3.8-27.6mm and 1.4-12.3mm respectively. The double calibration method appears to reduce the STA hence giving a more accurate representation of the anatomical movement and this may be the recommended method for reducing STA error in the future. Both of these studies were undertaken in only two participants and given the difference between the two participants the results need to be translated to a wider population to ensure applicability.

Benoit et al (2006) conducted the largest in vivo study on soft tissue artefacts on eight participants during walking and cutting activities. The comparison of the movement of two bone pins (distal femur and proximal thigh) with three markers attached, to that of four cluster markers on the thigh and shank demonstrated knee rotation errors up to 4.4° for walking and translational errors of up to 13mm. The largest error occurred in the abd/adduction angles but those for flexion/ extension and medial/ lateral rotation were very similar. These results differ from those of Stagni et al (2005) who found that there was less error in the flexion/extension direction. There were significant differences between the two marker methods for Flexion/ extension rotation angles, A/P translations and distraction/compressions (Benoit et al, 2006).

Using video motion analysis, O'Connor et al (1993) looked at the effect of marker placement deviations on spinal range of motion. They found that marker replacement error of up to 2.5 cm was acceptable. As the length of the lumbar spine is only 20-30 cm, this 10% error is large and these results should be questioned.

At present STA is an accepted error during motion analysis but researchers should be cautious and show care during anatomical landmark placement and reduce STA where possible.

4.1.2.2. Placement of the tool/ markers

Most of the static methods (Tools 1-6, Table 4.2, p68A) have limitations with reliability, accuracy or invasiveness and many are only capable of measuring hip or lumbar spine motion in one plane. They provide static measurements, resulting in a single value of the end range of motion. However they remain the basis for clinical measurement as they are, in the main, quick and easy tools to use so long as their limitations are taken into consideration. The findings by Mayer et al (1995) and Salisbury & Porter (1987) summarises the main issues with placement of the measurement tool.

Mayer et al (1995) studied the variance in the measurement of sagittal lumbar spine range of motion using three instruments. Fourteen examiners, of varied experience, measured the sagittal range of motion, using a dial fluid inclinometer, a kyphometer and an electronic inclinometer on 18 healthy subjects. Their results indicated that the intra-examiner reliability did not differ significantly among the examiners (F=1.39; df=13.319; p>0.05). There were no systematic advantages in using one instrument over another (F=2.05; df=1.319; p>0.05) and also the variability in each individual subject's measures were consistent across examiners (F=1.29; df=35.72; p>0.05). The authors suggest that the error does not lie with the instrumentation, but by inconsistent effort on the part of the subject or by change in the ROM through repeated measuring cycles as a result of stretching or voluntary effort.

This is not in agreement with Salisbury and Porter (1987), who pointed out that the cause of the error in determining a subject's full lumbar ROM from one examiner to another was due to the difference in instrument placement and in the inability to locate the necessary bony landmarks. They showed that those subjects in whom bony landmarks were difficult to find, as a result of adipose tissue concentration or a non prominence of bony features, were also those in whom they found large test/retest errors between examiners.

The accuracy of marker placement is a major issue (Walter & Panjabi, 1988) with potentially high measurement error, but it is expected that the gross error is less than 5° (Panjabi et al, 1982). Baker et al (1999) assessed hip rotation error with thigh marker placement offsets of ±30° reporting high variability depending on marker position. Thigh marker placement error also has an effect on the knee particularly in the frontal and horizontal planes and these authors recommend a thigh correction factor to minimise the effect of varied marker placement.

Nicol (1989) relates the problems identified for the taking of static measures to be similar for dynamic data collection and include: landmark positioning, skin movement errors and the correct plane of motion. Identification of bony landmarks, accurate placement of the measurement tool and ensuring pliability of the underlying soft tissue must all be taken into consideration towards good reliability of measurement.

4.1.2.3. Construct validity

Construct validity tests that what is being measured is true, and defines what is being measured Payton (1988).

Non-invasive skin-surface techniques for assessing lumbar spine showed good agreement with radiographic measurements of vertebral movements (Adams and Dolan, 1995). Portek et al (1983) looked at correlation between radiographic and two clinical measurements; the inclinometer and skin distraction technique for measuring lumbar mobility. Neither of these techniques correlated well with the vector stereography which gives a linear index of movement. The authors concluded that the external measurement techniques give indices of back movement but do not reflect true lumbar spine movement. Their study showed that the inclinometer provided a reproducible measurement but only with careful monitoring of the technique. As yet the construct validity of the dynamic tasks of walking, sitting to standing and bending forward have not been tested but it is generally accepted that all the tools discussed have good face validity.

4.1.2.4. Environmental problems

The tools outlined for measurement of static or dynamic measurement do not have any specific environmental issues such as temperature, humidity etc. However as for all measurement there should be consistency of use and a good operational definition should be employed to ensure a standardised environment.

4.1.2.5. Interpretation of data

Good interpretation of movement data is founded on understanding the process of data collection and the underlying mechanical and physiological issues. This is much easier for the clinical tools but is complex for data collected with both Optoelectronic Motion Analysis Systems and force platforms. The process of data 'cleaning' and processing depends on the software being used but will always involve some manipulation. The process of data cleaning to the stage of producing a stick figure can be tested by using an independent measurer to compare results ensuring repeatability and accuracy.

Both 'Specific issues within the tool' and observer error: Intra and Inter-rater will be discussed for the specific tools – sections 4.2.1 and 4.2.2.

4.1.2.6. Instrument choice

There is no one tool that can be classed as the 'best' or most accurate. Historical and financial issues have expounded the use of the tape measure and universal goniometers as standard clinical tools, but for research the more sophisticated

Optoelectronic Motion Analysis Systems must to be used to give detailed and accurate information on movement.

For this study an inclinometer was chosen to measure lumbar flexion and extension and a tape measure for measuring lateral lumbar flexion. The literature supports the choice. As an elderly population was to be investigated, as suggested by Moll and Wright (1971), all static range of lumbar spine motion, flexion, extension and lateral flexion were measured in standing position. To measure dynamic motion of the lumbar spine and hip during functional activities the Kinemetrix Motion Analysis System was used.

An intra-rater reliability study of the inclinometer and tape measure was completed prior to testing. Also a reliability study of marker placement, different spinal measurement system and verification of measurement of both the force platform and the motion analysis were undertaken (section 5.4 and 5.5).

4.1.2.7. Hip Joint Centre location

Hip joint centre location is the greatest source of error in movement analysis of the hip / pelvis and lumbar spine. This is particularly so for contact forces and force and moment generation. Delp and Maloney (1993) using a 3-D biomechanical model established that HJC errors of 2cm in any directions can cause miscalculation of force and moment generating capacity of muscles of up to 26%. This is particularly so for the abduction moment arm with a 2cm superior displacement error.

More details on the estimation of hip joint location are given in section 5.3.1. on the Hip program.

4.2. MEASUREMENT OF JOINT KINEMATICS

Objective joint measurement requires a body co-ordinate system to identify the three positions of origin (X, Y, Z) and the rotations around its axes by the amount of (θ_x, θ_y, θ_z) "*giving its spatial location orientation and at any time instant*" (Ladin, 1995, p4).

> *"Kinesiological measurements are aimed at quantitatively describing the spatial motion of body segments. The results can be used for the objective determination of the kinematics (the change of spatial co-ordinates with time) and for the calculation of the forces and moments that are associated with the motion (kinetics)"* (Ladin, 1995, p4).

Measurement of all six characteristics is required to allow calculation of the 3-dimensional joint centre movement. This, however, is difficult to achieve in anything but the laboratory situation, and measurement of joint movement in clinical practice is more likely to be a static measure either in one or two planes of movement. Measures of static single rotations (static movements in a single plane) gives inadequate information to assess joint loads and further data would need to be collected (Ladin, 1995).

Thus joint measurement falls into two main categories:

1. Simple static clinical measures which give estimates of single plane rotations,
2. More complex static or dynamic measures, which calculate true joint centre movement from laboratory gathered information, and can be used to assess joint kinematics and torques.

Table 4.2 (p68A) summarises the array of tools available to measure hip and lumbar spine movement.

Tools 1- 5: measure uni-planar static movements
Tools 6 & 7: measure both static and dynamic data (1- or 2-dimensions)
Tool 7: measures 3-dimensional movements
Tools 8-10: Systems can be used for static or dynamic assessment but measure true joint centre movement 3-dimensionally

The complexity of lumbar spine movement accounts for the numerous means available for assessing gross motion. Specific vertebrae movement can be measured by items 8 and 9 and will not be discussed. The lumbar spine comprises a number of individual joints, which compromises reliability and ease of use. The hip joint offers

Table 4.2 Clinical tools to measure hip and lumbar spine motion. Examples of research articles are given in brackets

Hip		Lumbar Spine	
1	Universal Goniometer (Roach & Miles,1991)	1	Universal Goniometer not possible for lumbar spine measurement
2	Inclinometer technique (Reference)	2	Inclinometer technique (Mellin, 1986a; Mellin 1989; Mellin et al., 1991; Newton & Waddell 1990)
3	Photography (Nonaka et al, 2002)	3	Photometry (Gill et al., 1988, Gajdosik et al, 1985)
		4	Modified Schöber skin distraction method (Moll & Wright, 1971; Fitzgerald et al., 1983; Mellin 1986b; Millar et al., 1992; Williams et al., 1993)
		5	Flexicurve / rule method (Burton, 1986; Tillotson & Burton, 1991; Lovell et al, 1989)
6	Electrogoniometers (Nicol, 1989; Rowe et al, 1989)	6	Electrogoniometers (Adams et al, 1986; Boocock et al, 1994; Paquet et al, 1991)
		7	Potentiometers (McGregor, et al., 1995)
	Both Hip and Lumbar Spine measurement		
8	Radiographic technique (Dvorak, et al., 1995; Pearcy et al, 1984; Portek, et al., 1983)		
9	Electromagnetic tracking (Lee & Wong, 2002, Pearcy 1993)		
10	Motion Analysis Systems (Syczewska et al, 1999)		

a larger degree of movement in three planes and is technically easier, but only if the pelvis and lumbar spine are stabilised. This study explores the issues of measuring the interaction of the lumbar spine, pelvis and hip joint during specific functional movement, addressing the reliability and validity of these measures.

4.2.1. Simple measurement tools

Krebs et al (1985) report that measurement of movements in the sagittal and frontal planes are easier to perform and more reliable than those in the transverse plane. The measurement tool is placed superficially either on the skin over the joint or on a distal part of the limb segment, thus the tool measures movement at a distance to the joint centre, and not true joint movement. Nicol (1989) suggests that the steps for consideration when taking goniometry measurements include the list below but these points are essential when using any of the measurement tools being discussed:

Position of subject for the test
Location of non-moving parts of the body
Alignment of the goniometer in the correct plane of motion
The correct identification of bony landmarks
The correct application of force for measurement of passive range of motion
The correct location of landmarks for the second positional location.

4.2.1.1 Universal goniometer

The Universal Goniometer is the clinical uni-dimensional tool to be used to measure range of motion in peripheral joints. Its design of a large 360° or 180° protractor with two arms of fixed length is not appropriate for the spine but it has commonly been used to measure hip movement. Modifications of this basic design for use on the spine are the spondlyometer (Ohlen et al. 1988; Pearcy, 1986) and the Kyphometer (Salisbury & Porter 1987) but the principle of measurement is the same. The reliability of these tools has not been extensively investigated but Burdett et al (1986) reports an intra rater Pearson correlation co-efficient of 0.7 for flexion and 0.51 for extension (p values not reported).

To measure hip joint movement, the centre of the Universal goniometer is laid approximately over the hip joint centre. For sagittal plane movement the centre is placed over the greater trochanter and on the anterior aspect of the hip joint for frontal plane. One arm is placed either down the length of the femur to the lateral femoral condyle or over the centre of the patella and the other lies either horizontally or across the pelvis.

Although the universal goniometer is the most extensively used instrument to measure hip joint movement (Norkin & White, 1995; Roach & Miles, 1991) there is little published research on reliability. Barbee Ellison et al (1990) assessed inter and intra-rater reliability of hip rotation in sitting using both a universal goniometer and an inclinometer. Using Intraclass Correlation Co-efficients (ICC), specific test not stated, they reported high reliability for all measures 0.95 to 0.98 for both patient (n=50 age 37.4±10.9yrs) and normal control groups (n=1000, age 26±5yrs).

4.2.1.2. Inclinometer or Clinical Goniometers

Inclinometers, gravity or clinical goniometers work on the pendulum principle, and are one of the primary tools for measuring spinal movement. They are not used extensively in measurement of the hip joint except for rotation, as reported in the last paragraph of the last section. Lee (2002) suggests that the inclinometer is the clinical method of choice when three-dimensional instrumentation is unavailable and when only spinal range of motion is required. The reliability of external measurement methods depends on accurate recognition of spinous processes for inclinometer placement particularly when excess soft tissue is present and knowledge of the variance of the normal spinal curves from individual to individual is required.

For measuring lumbar motion, in standing, the inclinometer is placed on the S_1 spinous process, the pointer allowed to settle, zeroed then transferred to the T_{12} or L_1 process, the difference between the readings is recorded as the degree of lumbar curvature (x). The procedure is then repeated after the movement is performed (y) and the difference (y-x) is taken as the degree of motion (Pearcy, 1986). This procedure also permits the measurement of posture.

Table 4.3 Intra-rater reliability of inclinometers - summary of literature

Author	Statistical test	Flexion	Extension	Lateral flexion
Reynolds (1975) ♦	PPMCC (r)	0.77	0.75	0.75
Burdett et al (1986) ♦	PPMCC (r)	0.73	0.15	
Merritt et al (1986) ♦	CoV (%)		50.7	
Newton & Waddell (1990) (EI)	PPMCC (r)	0.98	0.48	0.78

Key: ♦ static dial inclinometer, (EI) electronic inclinometer

To assess frontal plane motion, the inclinometer is placed on the contralateral aspect of the body to the direction of motion, at the $T_{2\text{-}3}$ level (Ohlen et al, 1988).

Using an inclinometer, Mellin (1986a) tested intra-tester reliability by measuring 10 subjects twice on consecutive days and one subject ten times. To evaluate inter-tester reliability, two testers measured 15 subjects on consecutive days. They calculated Pearson correlation coefficient (PPMCC) and intra-tester error (CoV). The PPMCC for measurement in the sagittal plane ranged from 0.86 to 0.91 and for lateral flexion from 0.57 to 0.91. Intra-tester and inter-tester reliability were comparable, but the intra-tester correlation coefficient for lateral flexion measurement was lower, i.e. less reliable. Many authors have reported intra-rater reliability data and these are summarised in Table 4.3.

Mellin (1986a,b) reported the most extensive study of lumbar spine reliability, and the results of other authors show similar trends except for Reynolds (1975) who showed that all movements have similar levels of reliability. Extension in all cases is less reliable than flexion. Intra-rater reliability measures are marginally lower than inter-rater and those for extension are particularly low, as this movement is particularly difficult to measure. Merritt et al (1986) in contrast found poor inter-examiner reliability (CoV=65.4%) for lumbar spine flexibility of 25 healthy subjects and an intra-examiner reliability of 50.7%.

Mellin et al (1991) also studied 27 subjects (mean 30.6 yrs) the effects of subjects' position on measurements of flexion, extension and lateral flexion of the lumbar spine. Their results indicated that flexion should be measured in the sitting position, extension in prone lying and lateral flexion against a wall. Lumbar forward flexion measured with an inclinometer in sitting and standing position showed no significant difference (t=0.38, df=195), but in sitting, hip and sacroiliac movement were eliminated, so that pure lumbar spine could be measured. It was suggested that subjects with impaired balance or physical skills as a result of age or disease might have problems with forward and backward bending in a standing position. Lumbar extension was found to be greater with support than without (Mellin, et al., 1991).

However, Moll et al (1972b) suggested that the prone position would require too great an effort and cause discomfort particularly in elderly subjects or those with OA. Extension of the lumbar spine measured in the standing position of the subject is invariably accompanied by secondary movements at the hip and SI joints (Moll, et al., 1972b). It is suggested that fixing the pelvis with hands on PSIS can prevent hip movement during spinal extension to 4.0±1.3° (Weisl, 1955).

The inclinometer or clinical goniometer was chosen for the measurement of lumbar spine flexion because of its good reliability. Although the reliability of extension was not good in the literature, pre-trial tests gave good results (Section 5.4.4) and therefore it was decided to use this tool. Lateral flexion was not measured in this way because of the inconsistency of placing the device.

4.2.1.3. Tape measure (Schöber technique)

Again a tape measure is only used for spinal measurement, as it is not feasible to use at the hip joint. Schöber in 1937 described a tape measure technique for measuring spinal flexion, which was slightly modified by Macrae & Wright (1969) and has been outlined by the AAOS (1988) as

> *"the definitive measurement of lumbar and thoracolumbar flexion as the tape measure adjusts very accurately to the thoracic and lumbar contours".*

The measurement technique is often called the skin distraction method.

Flexion

Three points are identified on the spine and marked: the centre of the lumbosacral junction is identified by the midline point that bisects the line joining the dimples of Venus and two points, one 5cm., below and the other 10 cm. above this point. This represents a 15cm starting measurement, the subject then flexes forward and the measurement is taken. The difference in the three points is taken as the unit of flexion. Macrae & Wright (1969) validation of the modified Schöber technique demonstrated that an error of 2cm above or below the midline markers would give an

Table 4.4 Reliability of Schöber technique (Merritt et al, 1986)

Movement	Intra-rater CoV(%)	Inter-rater CoV(%)
Flexion	6.6	6.3
Extension	9.4	11
Lateral Flexion	7.3	9.5
Key: CoV Coefficient of variation		

overestimation of 5±1.3° & 3±3.3° respectively and was independent of hip movement. Thus the modified technique is an accurate measurement tool.

Extension

Spinal extension is measured using the points above and in addition a plumb line is dropped from the upper point to the lower. The unit of extension is the distance travelled by the plumb line (Moll & Wright 1971).

Lateral flexion is measured from two points on the side of the trunk: the upper mark is the intersection of a horizontal line through the xiphisternum with the coronal line; and the lower mark is the intersection of a horizontal line through the highest point on the iliac crest with the coronal line. Again the difference before and after is taken as the measure of lateral flexion (Moll et al 1972). Merritt et al (1986) assessed the CoV using the Schöber technique (Table 4.4).

These results demonstrate that the Schöber tests produced low (<10%) CoV and therefore was able to reproduce measurements of the lumbar spine. The measures for extension are again not as reliable as flexion or lateral flexion. These reliability results are all of lower value than Reynolds' (1975) research but the trend is similar, the variation may be due to the measurement procedure and clinicians involved. Poorer reliability in extension and lateral flexion is mainly due to the problems of recording the position of the plumb line/ tape measure and the distance travelled. Thus the Schöber technique is predominantly used for flexion only.

Millar et al (1992) question the reliability of the Schöber technique because of difficulty in locating anatomical points, the relationship of skin distraction to underlying spinal movement and placement of skin marks. They caution the use of these techniques and encourage clinicians to ensure that the patient "warms up" prior to measurement and that a more rigorous anatomical identification system needs to be in place for measurement.

Lateral Flexion

Lateral flexion of the lumbar spine can also be measured by taking the distance calculated from the tip of the middle finger before and after it travels down the lateral aspect of the thigh during sideways bending (Norkin & White, 1995). Although care must be taken to place the participant with their back against a wall to ensure true lateral flexion without added flexion, it is an easier means of calculating the distance travelled during this movement (Moll & Wright, 1971).

Mellin (1986b) investigated the accuracy of measuring lateral flexion of the spine with a tape measure (n=476, age 44.9±5.4yrs). Results showed high intra-observer reliability for right and left lateral flexion ($r=0.96$; $p<0.01$) and high inter-observer reliability for right lateral flexion ($r=0.85$) and for left lateral flexion ($r=0.87$; $p<0.001$). Mean values and SD for right and left lateral flexion were 17.9±5.7 cm and 15.9±5.9cm, respectively.

Comparison of tape measure and Inclinometer data

In a later study Mellin (1989) compared tape measurements of forward and lateral flexion of the lumbar spine by analysing their correlation with the inclinometer technique, anthropometric factors and the extent of back pain related disability in 301 men and 175 women (no age given). Correlation of tape and inclinometer measurements with anthropometric factors showed that effects of height are minor, but weight, expressed as body mass index had significant positive correlation with tape measurement ($r=0.18$; $p<0.001$) and negative with the inclinometer measurement ($r= -0.19$; $p<0.001$) of forward flexion. A restriction of forward flexion associated with an increase of trunk tissue would be logical. A greater distraction between measurement marks accompanying an increase in weight is probably caused by more subcutaneous fat, and thus this causes a substantial bias of the tape measurements of forward flexion.

Both tape and inclinometer measurement had a positive correlation with lordosis ($r=0.28$ and $r=0.43$; $p<0.001$, respectively). The correlation between tape and inclinometer measurements of forward and lateral flexion also suggested that the tape measurement of lateral flexion is a better indicator of true spinal mobility, while inclinometer technique is a better indicator of true spinal mobility of forward flexion (Mellin, 1989). The shape of the base of the inclinometer makes its unsuitable for measurement of lumbar spine lateral bending (Anderson, 1982). Williams et al (1993) in a similar study compared the modified-modified Schöber technique (15cm not 10) with a double inclinometer method and found that the Schöber method was more reliable (test retest reliability 0.78 -0.89 flexion and 0.69 – 0.91 for extension). However the technique used was not standard and therefore their results may not be comparable with other studies.

Gill et al (1988) compared the repeatability of 4 measures of spinal movement: modified Schöber, finger tip to floor measure, two-inclinometer method, and a photometric method. The modified Schöber techniques had the best results with a co-efficient of variation for flexion of 0.9% in standing and 2.5% in sitting and 2.8% and 2.9% for extension respectively.

In this current study, for ease of use, the distance travelled by the fingertips was taken as the measure of lateral flexion.

4.2.1.4. Flexicurve (rule)

The flexicurve is a pliable metal band encased in a supple non-elastic plastic of approx. 61cm. in length and 0.8cm wide (Hart & Rose, 1986). The tool is only used for measurement of the spine and it is moulded to the spine at the vertical midline over the spinous processes, which delineate the region of the spine to be examined. The process is repeated before and after flexion and extension of the spine with the shape outlined by the flexicurve being traced onto a piece of paper. Tangents are then drawn at the level of S_2, L_4, T_{12} spinous processes and the angles of bisection are combined to give full flexion, extension and combined ranges of motion in degrees (Tillotson & Burton, 1991; Lovell et al, 1989; Walker et al, 1987; Burton, 1986; Hart & Rose, 1986). All authors report high intra-rater and inter-rater flexion reliability of r=0.96, 0.85 (Burton 1986), r=0.97 (intra-rater) (Hart & Rose 1986), r=0.84, 0.41 (Lovell et al 1989). Stokes et al (1987) reported excellent repeated measures reliability of the flexirule for sagittal plane measures (p=0.98) but disappointing results when these readings were compared with biplanar X-ray (r= 0.05). It should be noted that reliability has been found for flexion only and not for extension or lateral flexion. Although reliability of the flexirule is good for flexion, it is difficult to handle and mistakes can be easily made. Therefore it was not chosen for the present study.

4.2.1.5. Electrogoniometers / potentiometer

Electrogoniometers (EG) of various forms have been used to analyse joint movement during gait in the:

- **knee** (Johnson et al, 1982; Waugh et al, 1981; Townsend et al, 1977; Kettlekamp et al, 1970)
- **hip** (Nicol, 1989; Rowe et al, 1989; Gore et al, 1979; Smidt, 1971; Johnston & Smidt, 1970)
- **multiple joints** (Jansen & Orbaek, 1980; Lamoreux, 1971; Finlay & Karpovich, 1964).

Mafiana Nwaobi (1986) outlines a potentiometer for measuring continuous hip position in children with cerebral palsy to assist with establishing an appropriate, individualised adaptive seating position.

The electrogoniometer mentioned are of four main types:

a) jointed frame work (Lamoreux, 1971; Finlay & Karpovich, 1964),
b) flexible mercury (Johnson et al, 1982)
c) step goniometers (Roth et al, 1981)
d) Strain gauges (Biometrics Ltd) (Rowe et al, 1989; Nicol, 1988).

Electrogoniometers are an adaptation of a potentiometer with an electrical supply attached to a data collector which permits the translation of electric current or electronic signal from a counter, to a standard unit of measurement (degrees). The movements measured will either be single (Rowe et al, 1989; Tata et al, 1978), twin (Boocock et al, 1994) or three dimensional (Laubenthal et al, 1972; Chao 1980).

The hip joint in particular is very difficult to measure with an EG as it has no fixed point for attachment, with the pelvis and thigh moving relative to each other. However EGs have been used for lumbar spine evaluation (Paquet et al, 1991; Boocock et al, 1994; Adams et al, 1986), measuring total lumbar spine movement rather than pure joint movement because the goniometer is placed on the skin over the whole of the lumbar spine. The greatest advantage of this type of system is that it measures dynamically and therefore can determine angular velocity as well as a range of movement.

In the lumbar spine, Paquet et al (1991) report the reliability of an electronic potentiometer on 10 normal subjects for lumbar flexion. The correlation coefficient for validity against an inclinometer was r=0.97 and a Pearson's correlation coefficient of r=0.99 for intra-rater reliability, over 60° of movement. Boocock et al (1994) recorded lumbar spine reliability of a number of measurement tools. Comparison of the standard universal goniometer and the Biometrics Ltd electrogoniometer gave a correlation coefficient of r=0.96 and an intra-rater correlation coefficient of r= 0.78 for anterior flexion and r= 0.92 for lateral flexion. The correlation coefficient for anterior flexion between the electrogoniometer and an inclinometer was r= 0.99 and with a flexicurve r= 0.77. It should be noted that the maximum degree of motion, in any plane, was 40°. The electrogoniometer did not cause any discomfort or inhibit motion but the authors commented that skin fixation was very important and that attachment with inelastic tape reduced skin movement (Boocock et al, 1994).

Gore et al (1979) produced one of the earliest electrogoniometers for use at the hip joint using a pelvic girdle with transducers placed over the centre of the head of femur. The movement graphs obtained displayed consistent data, which replicates that from other devices, but no comparisons have been made and no numerical data was given for review. Rowe et al (1989) collected uni-dimensional data from the hip joint during gait using an early version of the Biometrics Ltd twin axis strain gauge electrogoniometer. Data was correlated against a video analysis system, demonstrating an overall standard deviation of 2° (Rowe et al, 1989). The authors

Table 4.5 Comparison of Biometrics twin axis strain gauge electrogoniometer

	Lumbar spine			**Hip**		
	BEG	Kinemetrix	Diff	BEG	Kinemetrix	Diff
Mean (°)	56.24	55.65	0.59	43.38	47.93	-4.55
SD	2.21	3.48	2.43	8.96	3.89	8.32
T-test	0.77, p=0.23			-1.73, p=0.059		
CoV (%)	3.93	6.26		20.65	8.12	
LoA+ (°)			6.09			14.28
LoA- (°)			-4.91			-23.37
Range (°)			11.00			37.65
Key: BEG Biometrics Ltd Electrogoniometer, CoV Coefficient of Variation LoA+ Limits of agreement (upper limit), LoA- Limits of agreement (lower limit)						

concluded that the strain gauge goniometer was an effective tool for measuring patterns of motion up to 110°.

The disadvantage of the electrogoniometer is the difficulty of skin attachment. If strong attachment is undertaken this may alter joint motion because of soft tissue restriction caused by the bonding (Coutts, 1998). This is particularly true for movements at the hip joint where it is surrounded by soft tissue with no easy accessible bone landmarks for attachment (Ladin, 1995). Mechanical electrogoniometers can also prevent free joint movement because of the nature of the device and its attachment. Thus although the electrogoniometer is an excellent measurement tool, its use at the hip joint is limited.

Comparison of active hip and lumbar spine movement, in 10 healthy participants, measured simultaneously with both the Biometrics Ltd twin axis strain gauge electrogoniometer (BEG) and the Kinemetrix motion analysis system identified some differences (Table 4.5) (Coutts, 1998). Lumbar spine movement was comparable (p=0.23), with almost identical mean values and low standard deviations and CoVs. The BEG was more variable in its measurement of the hip (p=0.059, CoV 20.65% for BEG, compared to 8.12% Kinemetrix), and consistently measured lower than the motion analysis system (Table 4.5).

The LOA for direct comparison of the two tools indicated that the range for the lumbar spine (11°) was just acceptable but for the hip the range was too large to be considered reliable in clinical measurement (Coutts, 1998). Data collected by the BEG and Kinemetrix motion analysis were not interchangeable when measuring the hip joint movement but were for the lumbar spine. The electrogoniometer was not chosen for use in the present study.

4.2.1.6. Radiographic techniques (X-ray) & scanning

X-ray and scanning techniques allow the recording of the position of the bones constructing a specific joint i.e. pelvis and femur for the hip joint, L_4 & L_5 for a specific part of the lumbar spine. Measurements of bone on scan or X-Ray at or through the range of movement gives the most 'valid' measure of joint movement without the interference of muscle, subcutaneous fat or skin movement.

There are few examples of X-ray analysis of hip movement as interpretation of this joint by X-ray is not necessarily required. For the multi-joint motion of the lumbar spine movement, X-ray analysis helps the understanding of the complexity of spinal motion. Validity of lumbar spine motion is much more difficult to establish and X-Ray techniques remain the main reliable 'gold standard' comparison (Loebl, 1967), although X-rays, at the moment, can only be taken at the beginning, end and set points in the movement and not concurrently. Three-dimensional X-ray analysis was used by Pearcy et al (1984) to study normal static movement in the lumbar spine, using 11 healthy young males (mean=29.5yrs). The reliability of this technique is not known but it remains a valuable and valid contribution to clinical measurement of the lumbar spine. Unfortunately there are considerable ethical problems with radiation levels involved and therefore this technique cannot be used on an ongoing basis.

Magnetic Resonance Imaging (MRI) gives a detailed and safe means of investigating altered joint structure in static positions at the end or through range, although accessibility is very difficult and costs are high. The emergence of MRI scanners, which permit dynamic data collection, will allow much greater freedom to assess joint movement but at this time the techniques are expensive and rare. As gross functional movement was being measured in this study X-ray and MRI were not considered.

The alternative means of measuring static movement is to use an Electromagnetic or an Optoelectronic motion analysis system. This instrumentation can be used to measure static or dynamic movement either two or three-dimensionally and is particularly useful for measurement of more complex activities.

4.2.2 Complex measurement tools

Evaluation of dynamic movement is restricted to Video, Optoelectronic motion analysis or Electrogoniometery. Each of these has restrictions for use in clinical practice and involves greater expense than the tools for static movement. Electrogoniometery has been discussed earlier as it is predominantly used as a two-dimensional measure. The advantage of Optoelectric and video systems is that complex movements can be measured dynamically with accuracy in all planes simultaneously and with the possibility of real time analysis. With advancements in technology, new instruments have been developed which are capable of assessing dynamic lumbar spine motion (Pearcy & Hindle, 1989; Hindle et al., 1990). These include 3-D Space Hybrid System (Buchalter et al., 1988), 3-Space Isotrak (van Herp et al, 2000; Dolan and Adams, 1993), CA-6000 Spinal Motion Analyser (McGregor, et al., 1995), and Optoelectronic measuring system (Syczewska et al, 1998, 1999; Thurston & Harris, 1983).

4.2.2.1. Electromagnetic

Electromagnetic devices use sensors applied to trunk or limb segments to give the relative change in position between these points in three dimensions. This type of instrument is particularly used for spinal measurement as ease of fixation and data collection allows measurement of both gross spinal movement and individual spinal segment motion (van Herp et al, 2000).

Dolan and Adams (1993) used the electromagnetic 3-Space Isotrak device and found it gave accurate values of lumbar flexion. Readings tended to be exaggerated if the leads run over the shoulders probably as a result of excessive movement of the leads causing interference (Hindle et al., 1990). Pearcy (1993) reports that because of skin movement under the attachment of the electromagnetic sensors of the Isotrak, measurement of axial rotation produced larger readings when compared with the X-ray method. Similar results were found by Mannion and Troke (1999). Although electromagnetic instrumentation would have been appropriate for this study, this was not available and a motion analysis system was used.

4.2.2.2. Motion analysis systems

The motion analysis systems used today developed from the early photographical assessment of movement undertaken by Muybridge in 1887, who recorded horse locomotion using a series of still cameras along a racetrack. Marey, from 1873, used a moving camera at a greater frequency, and more importantly introduced the use of markers, with white strips on a black suit, to more clearly identify body segment movement (Ladin, 1995). Sutherland & Hagy (1972) were amongst the first to investigate human walking using photography.

The image from a camera projects a 2-dimensional image only but joint and body movement is 3-dimensional. Optoelectronic motion analysis take the 2-dimensional images and create a three-dimensional stereophotogrammetric reconstruction by either combing the information originating from projections of the point onto two planar cameras, or combing three independent linear co-ordinates from one-dimensional cameras (Ladin, 1995). To identify segment position to allow data collection, either active or passive markers are attached to the body, singly or in clusters. The majority of systems use passive markers where reflective tape over spherical markers, reflect projected light giving representation as a bright spot on a video screen. Manual or automatic identification of the reflected spots to the representative segment markers followed by photogrammetric reconstruction gives the spatial location of body. The body location is then represented as either a moving 'stick figure' or the specific data is collated to give a numerical or graphical representation of joint movement over time.

By assigning an embedded co-ordinate system to the proximal and distal segments the system uses positional data to calculate 3-dimensional angular motion at specific joints (Woltring, 1991; Grood & Suntay, 1983). Euler angles (Chao, 1980) or helical axis definitions (Woltring et al, 1985) are then used to compute the relative rotations between the embedded co-ordinate systems. Euler angles were used in the current study to give relative rotations between segments including: flexion/extension, abduction/adduction and axial rotation in sequence (Ramakrishanan & Kadaba, 1991). The second and third rotations are always defined in respect to the first, the accurate orientation of the first axis is crucial (Ramakrishanan & Kadaba, 1991).

There is limited published research on the reliability of the Kinemetrix Motion Analysis System so reliability of the Kinemetrix motion analysis systems was tested as part of the set up of the current investigation. The accuracy was measured as the first part of the present study (Thornton et al, 1998) and is reported in section 5.4.2. Ehara et al (1995) assessed the ability of eight motion analysis systems to statically measure two stationary markers placed at a known distance. They also measured the time for processing data from gait analysis using five markers. The Kinemetrix motion analysis system demonstrated an error of 3±3.8mm for the static distance test with an absolute error of 3.3mm. The processing time for gait data was one minute. Amongst the five passive marker systems tested, the Vicon Motion analysis system was the most reliable, closely followed by the Elite and the Kinemetrix systems. It should be noted that the data for the video (Quick mag & Video Locus) and active marker (Optotrack) systems tested had less error and took a shorter time to process.

The reliability of the Vicon Motion Analysis system has been reported in an extensive study by Kadaba et al (1989). Using the coefficient of multiple correlation(s) (CMC) these authors reported that hip, knee and ankle joint movement in the sagittal plane had excellent repeatability for both within and between day measurements (0.996 – 0.964), whilst pelvic tilt had the lowest reliability 0.643 (within day) and 0.649 (between day). Frontal and transverse plane movements had lower values than the sagittal CMC. All CMC values were better for within day tests than between day. Kirtley (1998) also found that the best reliability was found for: temporal-distance parameters, sagittal joint angles, sagittal joint moments, foot progression angle, hip frontal joint power and foot, knee and hip transverse moments.

Poor reliability was identified for pelvic rotation, all transverse joint powers, ankle and knee frontal powers and foot frontal moments. Pelvic tilt & obliquity, all sagittal joint powers and hip frontal moment all had adequate reliability. These results are very similar to those of Kadaba et al (1989) and it can be suggested that if the most reliable system gives these levels of reliability then other systems should at least display similar trends. Whatever the measurement system used, the technique is open to error. High variability has often been found in motion analysis data (Cheng

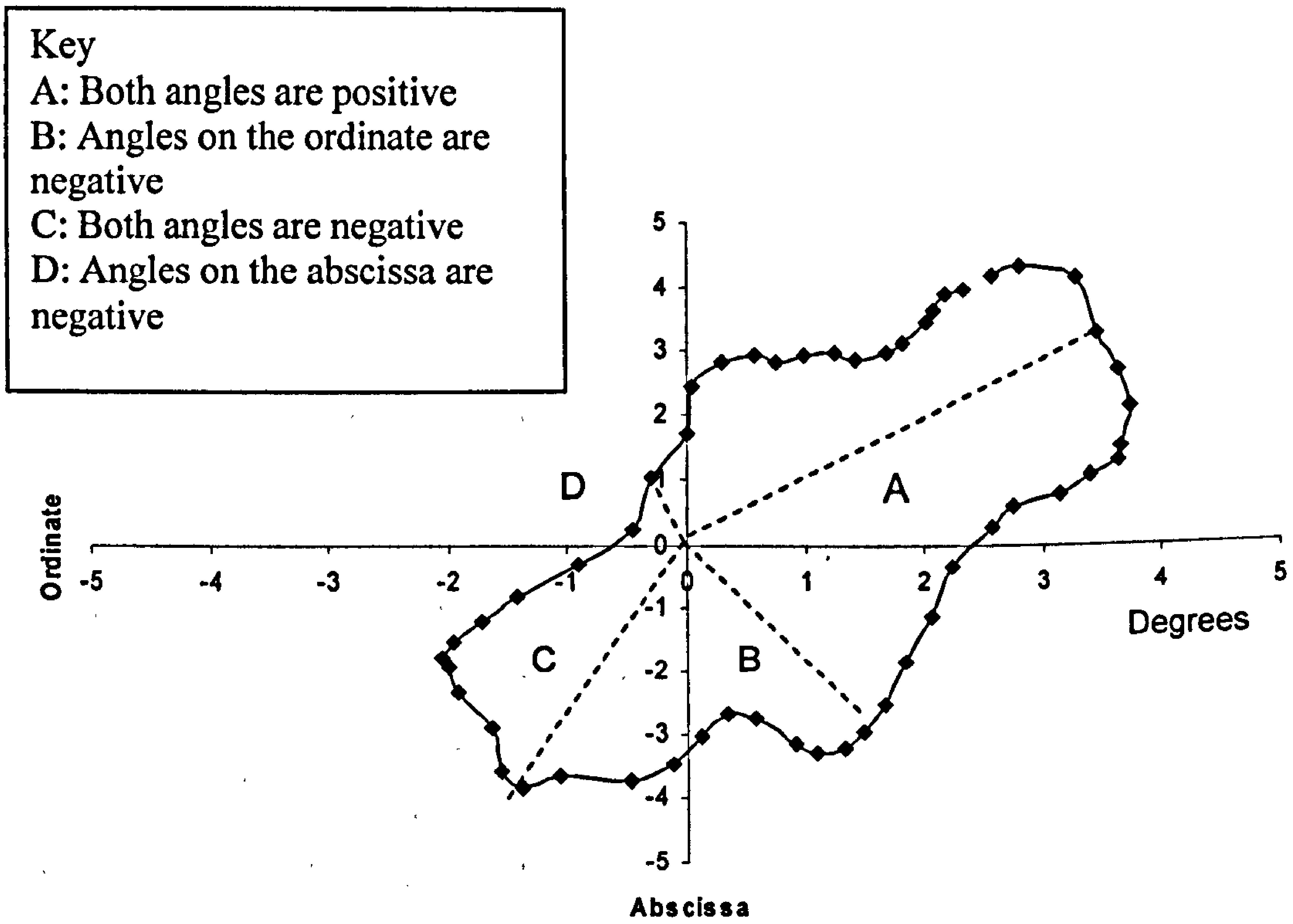


Figure 4.1 Geometrical representation of an angle-angle diagram (time interval in seconds.) All data measured in degrees.

et al, 2000) and this leads to poor repeatability and a lack of awareness of normal ranges in both healthy and pathological populations.

4.2.3 Presentation of kinematic data

Movement can only be fully understood once is has been through the three stages of collection, presentation and analysis. The first stage has been discussed but the second stage needs to be considered. The presentation of Biomechanical data has historically been undertaken in a 2-dimensional format in a number of different styles. The most commonly used are angle-time and angle-angle diagrams where angles are plotted against time or against another angle, giving the reader a view of the interplay through a movement cycle.

Angle-angle diagrams or graphs

These diagrams demonstrate the relationship between movements by exploring the shape produced relative to the graph axes. The angle from one plane or limb is plotted on the x axis (abscissa), and the angle form the other joint or limb on the y axis (ordinate), with the units of movement in degrees. Either one or repetitive cycles of movement can be recorded on the graph by a continuous line and it is the shape tended by this line that is assessed to explain the relationship between the joint angles. Points on the line in the upper right quadrant of the graph would indicate that both joint moved in a positive direction (A, Figure 4.1), whilst the opposite occurs in the bottom left hand quadrant, with both angles being negative(C, Figure 4.1). In each of the other quadrants one set of angles is in the negative direction; in the top left hand quadrant angles on the abscissa would be negative (D, Figure 4.1), and in the bottom right hand quadrant ordinate angles will be negative (B, Figure 4.1).

The slope of the line joining any point to the origin is representative of the resultant angle at that moment of time in the movement cycle and if angles are equal in both directions the resultant angle will be near 45° or equivalent in each quadrant (45°, 135°, 225° or 315°)(B, Figure 4.1). If one joint angle is greater than the other then the resultant angle will tend towards the axis of this angle e.g. nearer to 0°, 90°, 180°

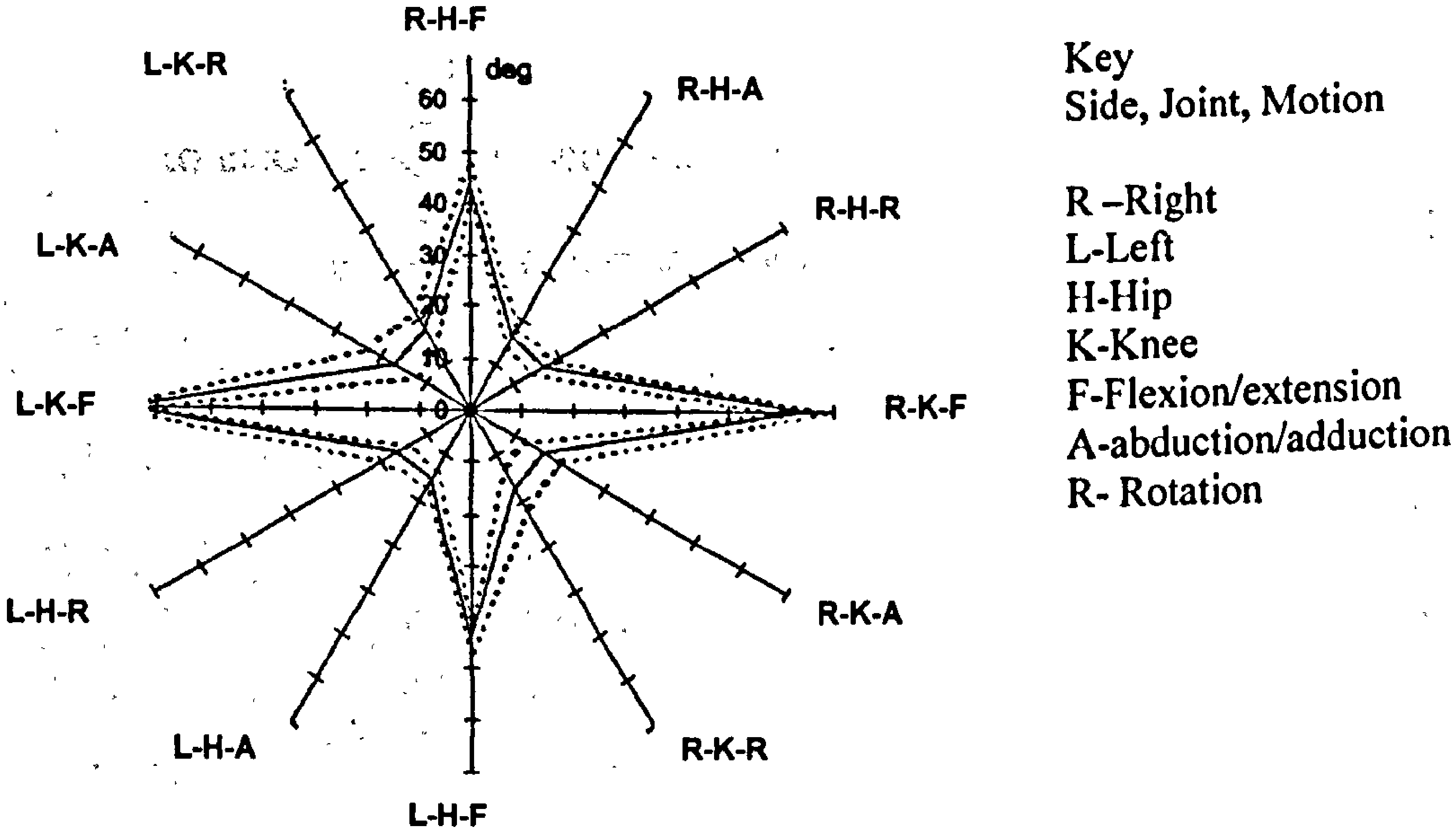


Figure 4.2 Muliplot graph of mean hip and knee range of motion from 13 controls (adapted from Cheng & Pearcy (2001)

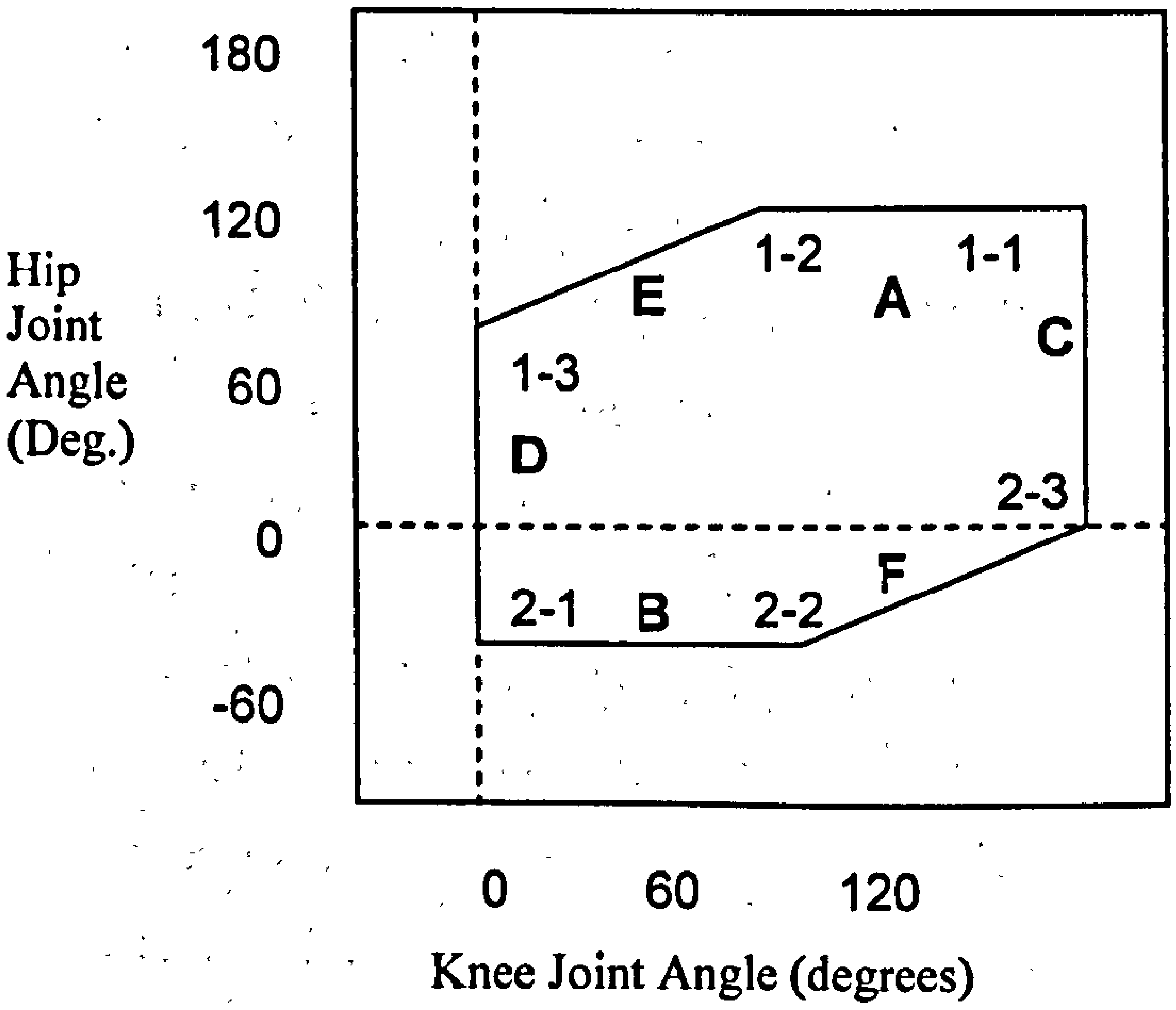


Figure 4.3 Geometrical representation of the interaction between passive hip and knee movement. (Nonaka et al, 2002). Modified angle-angle diagram.

Key

1-1: maximal flexion and extension at hip
1-2: knee extension in maximal hip flexion
1-3: hip flexion in full knee extension
2-1: maximal flexion and extension at knee
2-2: knee flexion in full hip extension
2-3: hip extension in full knee flexion

or 270°(C, Figure 4.1). If the line is marked by time intervals from data collection then the closer the points are to each other indicated that more time has been spent at this portion of the movement curve e.g. upper and lower lines in quadrant A, Figure 4.1., in gait this is likely to be during the stance phase. Moment-angle diagrams have also been reported by Frigo et al (1996) where one axis records joint moment or resultant, the other the degree of motion, but these types of graphs are not often used.

It has been argued that the traditional presentation of an angle-angle diagram (e.g. Figure 4.1) do not give a complete picture of the data and that other forms are needed to allow clinicians to undertake analysis and decision making more efficiently (Loslever & Barbier, 1998). Loslever and Barbier suggest the use of star diagrams to display a more complete picture of gait rehabilitation. They plotted normalised local distance indictors for three sagittal plane movements (hip, knee, ankle) and three moments (F_x, F_y, F_z) over five weeks of weekly measurements, to give an overview of change for a particular patient. These authors suggest that this presentation gives a more global view of change and makes decision making easier for clinicians. Cheng & Pearcy (2001) also reported the use of star diagrams (multi-axis graph plotting) to record range of hip and knee motion during gait (Figure 4.2) and they report that this type of representation is easy to understand and interpret. However at this stage there is little data for comparison and the Cheng & Pearcy study was based on gait 6 months following THR.

Cappozzo (1981, 1984) describes the use of Lissajous's plots to show linear displacement of head and trunk during walking. Here directional displacement through the movement can be represented on two axes e.g. forward and back displacements are plotted against those going up and down, to give a representation of a movement pattern in two planes. There is no time element in these plots and therefore giving simple regularity. Repeated cycles can be superimposed on each other to show repeatability. Event markers such as toe off, heel strike can then be represented on the movement pattern line to give a clearer picture relative to the motion being observed.

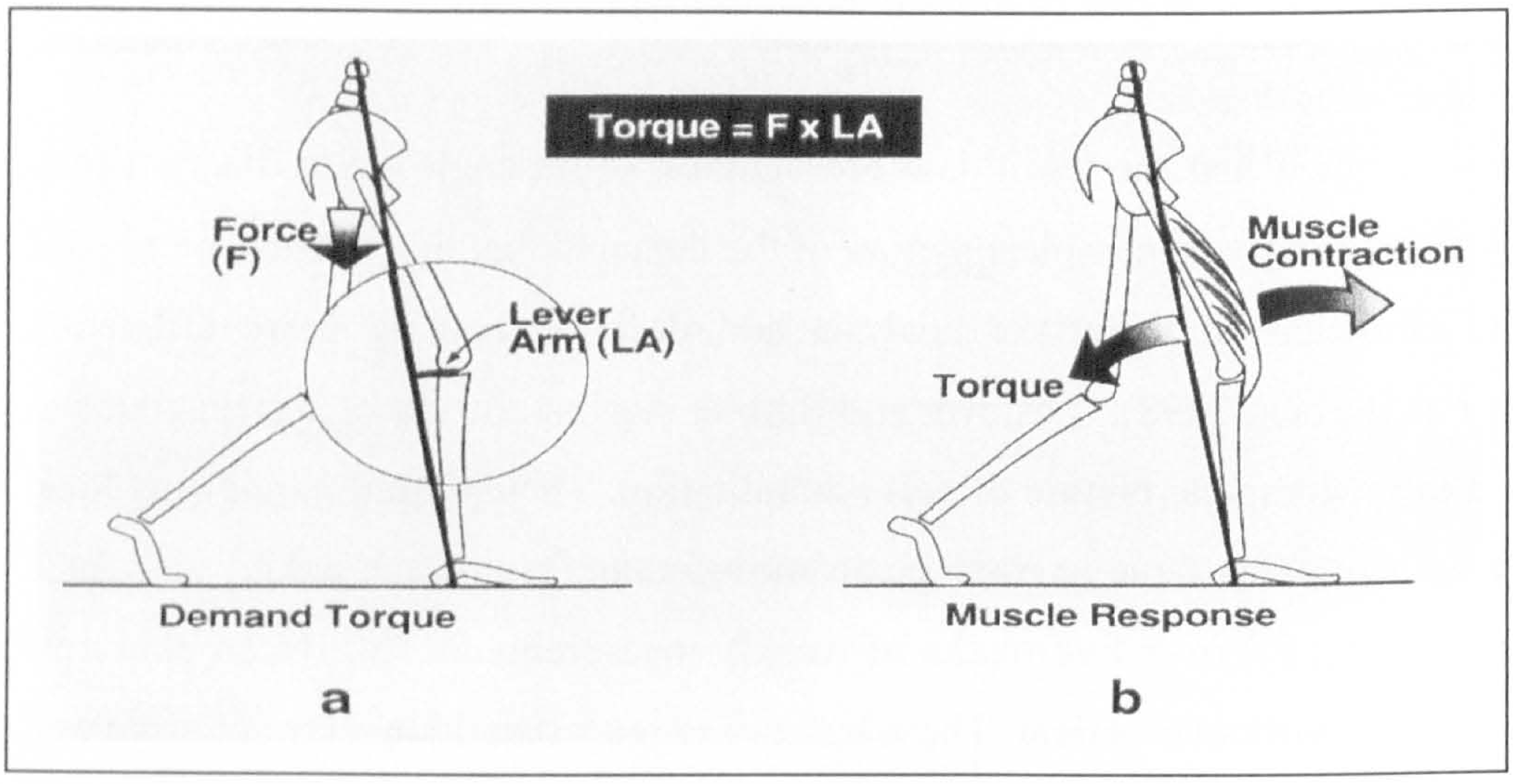


Figure 4.4 Torque demands
(a) External reaction force
(b) Opposing internal reaction force (Perry, 1992)

Using geometrical representation Nonaka et al (2002) display the interactive mobility of the hip and knee in the sagittal plane (Figure 4.3, p83A). Passive hip and knee movement are represented on the six vertices with maximal flexion and extension at both the hip and the knee at points 1-1 and 2-1 respectively. Point 1-2 represents the limit of knee extension while maintaining maximal hip flexion, point 1-3 is the point at which the hip joint cannot be flexed further while maintaining full knee extension; both these points are influenced by the length of the hamstrings. Points 2-2 and 2-3 have the same limitations but are influenced by the length of the quadriceps muscles. Thus the interaction between restraints to passive movement at the hip and knee can be assessed graphically.

Angle-time and angle-angle diagrams will be used to explore gait cycle data in this study.

4.3 KINETICS

Kinetics is the measurement and analysis of forces, powers, and energies of movement e.g. ground reaction forces, joint reaction forces, moments of forces, tendon forces, joint contact force, power, work and energies. Winter (1987) describes kinetic variables as:

Reaction force: the resultant force acting on or at any point in the skeletal system. The internal reaction forces at any point are in static and dynamic equilibrium with the externally applied forces and the inertial forces distal to that point (unit = Newton (N)) and is normally calculated at joint centres. The **Ground Reaction Force** is the resultant of the combined external reaction forces and is often represented by a vector (Figure 4.4). The external torque demands require opposing dynamic and passive internal force generation from soft tissue to maintain postural equilibrium, pictorial representation of this can be seen in Figure 4.4.

Joint contact force: vector summation of all forces acting at a joint. It is the summation of the reaction forces at that joint plus any compressive or shear forces due to the muscles, ligaments or structural constraints acting at that joint (unit =

Newton (N)). Although direct measurement of normal hip joint forces is not possible, force transducers have been inserted into the femoral head of the total hip prosthesis (e.g. Krebs et al, 1998) to give direct force measurements.

Moment of force: resultant of all forces acting at a distance about an axis of rotation and which causes an angular acceleration about that axis (unit = Newton*meters (Nm)). To allow comparison between individuals the moment of force is normalised by dividing by body mass and are reported as Nm/kg (Winter, 1987). Joint moments of force are the net result of all internal force acting at that joint and include the moments due to muscles, ligaments, joint friction and structural constraints. These are either in static or dynamic equilibrium with the external moments due to externally applied and inertial forces distal to that joint.

At the hip joint there are three joint reaction forces along three axes, utilising six equations to describe the three-dimensional kinetics during movement with six degrees of freedom. Each spinal segment also has six degrees of freedom again with three joint reactions and three moments.

External joint forces are calculated using data from force platforms, force transducers and known values of body mass, body segments etc (Röhrle et al, 1984; Crowinshield et al, 1977 & 1978b; Paul, 1967). From the external forces, known values and mathematical modelling the internal moments can be calculated and estimations can be given of the work that muscles and soft tissues undertake to control joint movement. Some authors have compared the force values from calculated hip joint forces to those measured through instrumented hip prosthesis (Stansfield et al, 2003). For the purpose of this thesis only internal forces and moments will be discussed, during functional tasks.

From the literature numerous methods of normalising joint moments are offered with the commonest being; body mass (Kuster et al, 1995; Winter, 1987), body weight * height or body weight * leg length (Moisio et al, 2003) or impulse (DeVita & Hortobagyi , 2000). The leg length and height methods could be taken as being very similar as there is a strong relationship between the two measures. Moisio et al (2003) calculated joint moments using non-normalised data as well as body mass and body weight * height methods of normalising on 158 participants. Height and weight accounted for 7-82% of the inter-subject variability in non–normalised data compared to 6% when normalised. Joint moments for hip adduction (normalised by body weight* height) and ankle moment (normalised by body mass) were the exception to this very large decrease. Height and weight accounted for 16% of the variance for the hip adduction when normalised by body weight* height and it is suggested that height may not be the best variable to use for normalisation for frontal plane moments, but that pelvic width may be more representative. The results of the study by Moisio et al (2003) show that either the body mass or body weight* height methods are effective in normalising joint moments but that the body weight* height method is better at reducing gender differences. As leg length can be correlated to height, these authors suggest that this measure may be used as an alternative to height.

For this study normalisation of joint moments was undertaking using body mass, because there is no literature at this time to compare Nm/(BW*height) for this population.

4.4 HIP AND LUMBAR SPINE KINEMATICS AND KINETICS DURING WALKING IN NORMALS

As discussed in section 3.2.3 the lumbo-pelvic-hip complex is paramount for normal movement and function (Lee, 1989). This section explores how three body segments; the hip, pelvis and lumbar spine, perform during gait, as a function which has been recognised as being problematic to those with hip and spinal pathologies (MacWilliam et al, 1996; Munin et al 1995; Zavadak et al, 1995).

Measurement of hip motion has been gathered for each of these functions but lumbar spine motion and kinetic data has not been, therefore only where appropriate will lumbar spine and hip kinetics be presented.

Table 4.6 Basic temporal gait parameters: reference data for normal subjects, 60 - 79 years (Öberg et al, 1993)

	Male	Female
Mean (SD)	**Gait Speed (m/s)**	
60 - 69 yrs (n = 15)	1.28 (1.24)	1.16 (0.17)
70 - 79 yrs (n = 14)	1.18 (1.54)	1.11 (0.13)
	Step Frequency (steps/s)	
60 - 69 yrs	1.95 (0.14)	2.06 (0.18)
70 - 79 yrs	1.91 (0.14)	2.03 (0.14)
	Step Length (m)	
60 - 69 yrs	0.65 (0.04)	0.55 (0.04)
70 - 79 yrs	0.62 (0.05)	0.54 (0.03)

Walking is characterised by two main events: stance and swing. Within these events the stance phase has five phases: Heel Strike (Initial Contact) (0-2% gait cycle (GC)), Loading Response (2-10% GC), Mid Stance (10-30% GC) and Terminal Stance (30-50% GC) and Pre Swing (50-60% GC), the swing phase has three phases: Initial Swing (12% GC), Mid Swing (14% GC) and Terminal Swing (12% GC) (Perry, 1992). Within the events there are three basic tasks: weight acceptance and single limb support as part of stance phase, and limb advancement as part of swing phase (Perry, 1992).

Commonly reported gait analysis parameters are walking velocity, cadence, spatial and temporal characteristics of the feet, linear and angular kinematics of the hip, knee, ankle, foot, shank, thigh and pelvis (Kirtley, 2006; Rose & Gamble, 2006; Winter, 1987). Temporal characteristics for non-THR adults for 60 – 79 year olds are presented in Table 4.6. Watelain et al (2000) suggest that gait characteristics in the older population can be divided into three categories when compared to the young: 1) slower walking speed due to a shorter stride, 2) slower walking speed due to reduced cadence and 3) maintain walking speed with increased cadence. All three of the groups potentially result in altered mechanics at the hip and lumbar spine segments.

Gait analysis has been predominately concerned with the movements of the lower limbs and pelvis (Nottrodt, et al., 1982; Saunders, et al., 1953) and it is only in the last few years that the spine has been included in three dimensional measurements. The interaction between these body segments is in the upright position, the lumbar spine and hip movements during gait will be discussed separately.

4.4.1 Lumbar segment

Motion of the lumbar spine is an integral aspect of human gait not yet fully explored. The importance of the trunk in walking was emphasised over forty years ago, but it is only recently that the lumbar spine has been assessed three-dimensionally (Crosbie et al, 1997a,b; Thurston & Harris, 1983). Crosbie & Vachalathiti (1997) suggest that *"the relative timings and synchronies of motion in the pelvis and hip joints is important in the production of a fluent gait pattern."*

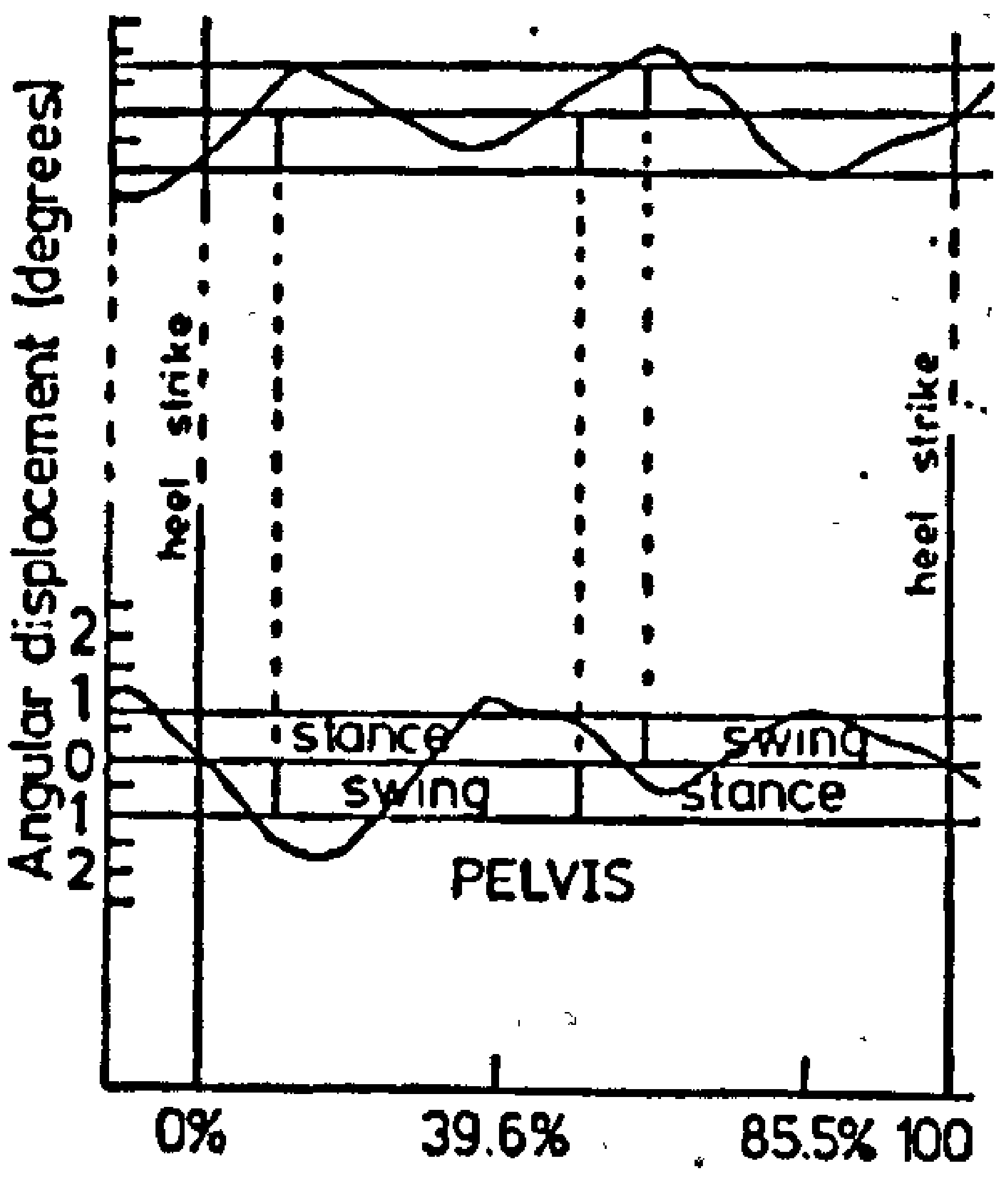
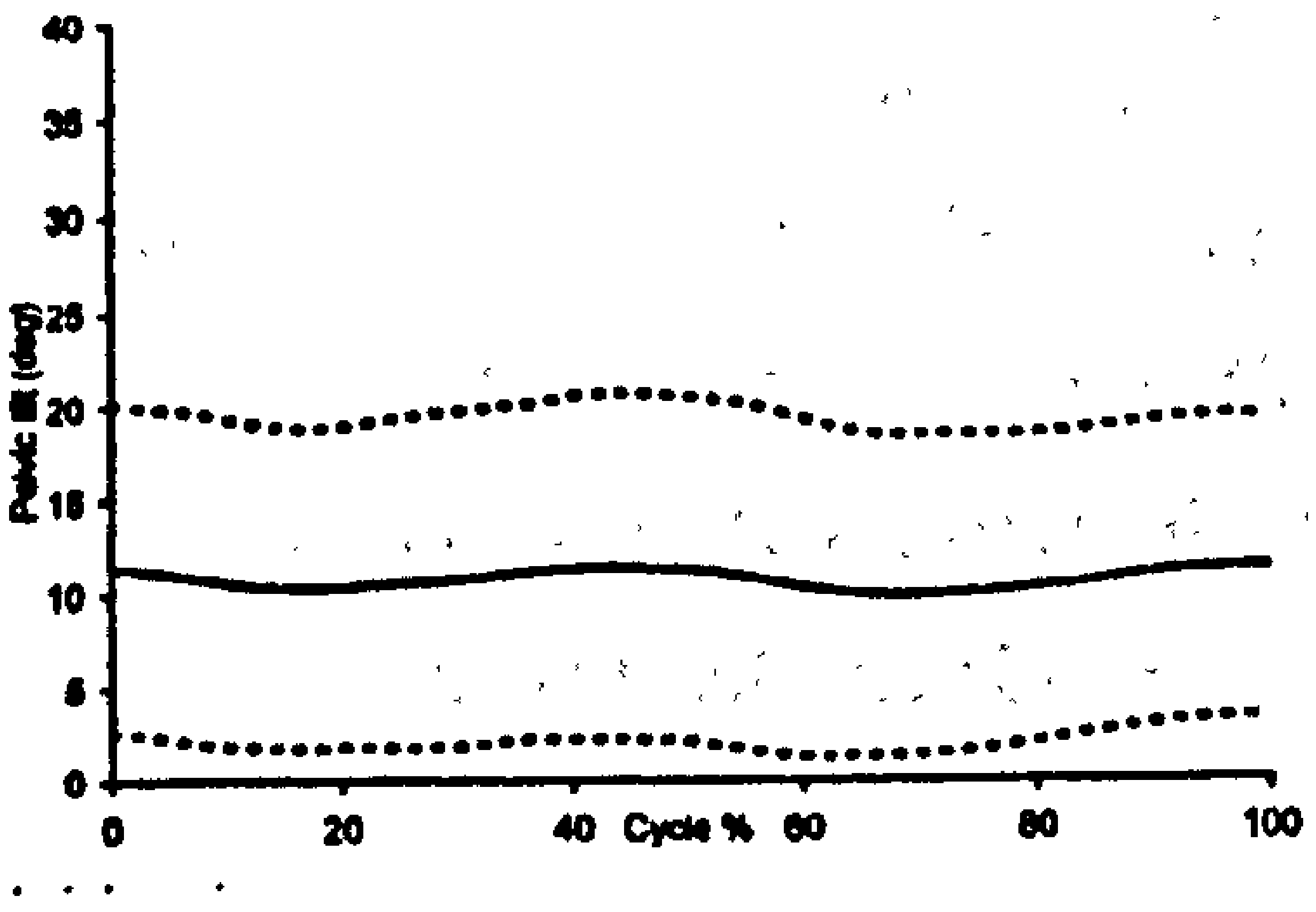
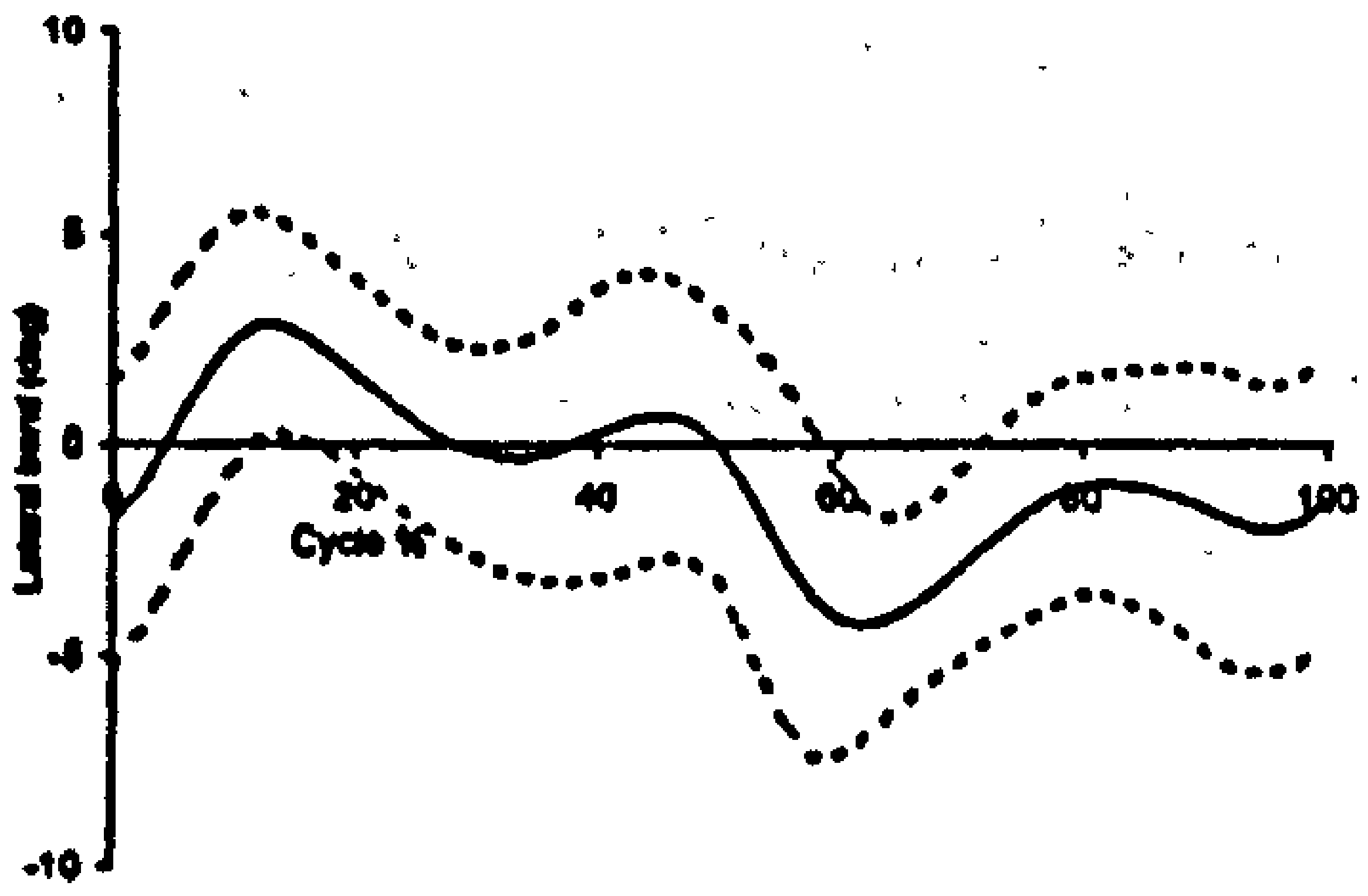


Figure 4.5 Thurston and Harris (1983) Sagittal plane movements of the pelvis and lumbar spine



a) Pelvis



b) Lumbar Spine

Figure 4.6 Whittle and Levine (1999) Sagittal plane movements of the pelvis (a) and lumbar spine (b)

As the lumbar spine and pelvis work as a unit it is difficult to look at the lumbar spine in gait without discussing pelvic motion.

4.4.1.1 Pelvis

Mean patterns of sagittal plane pelvic and lumbar spine movement are represented in Figure 4.5 & 4.6.

Saunders and co-workers identified six major determinants of gait and reported that three of them are related to motion of the pelvis. Rotation of the pelvis around the vertical and sagittal axes were fundamental for walking by affecting a clear pathway for the advancing limb and reducing displacement of the centre of mass (COM) thus the conserving energy (Saunders et al, 1953). Lateral displacement of the pelvis was the third determinant to influence walking. Overall range of motion of the pelvis averaged 4° in the sagittal plane, 7° in the frontal and 10° in the transverse plane (Perry, 1992). Murray (1967) however cautions that pelvic movement, amplitude, timing, and pattern of movement are highly variable between participants. Kerrigan et al (2001b) showed this variability in their study of 30 participants aged 24.6±4 yrs along with a trend for women to have a greater degree of pelvic rotation (transverse plane) than men (4.5±2.3° vs 4.1±2.3° respectively). These authors also question the relationship between pelvic rotation and reducing vertical displacement of COM in walking, as described by Saunders et al (1953), as pelvic rotation accounted for only 12% (2.5±1.1mm) of the reduction in COM displacement in their study.

Judge et al (1995) measured 26 healthy older adults (mean 79±6 yrs) showing movement of pelvis as: mean pelvic tilt in sagittal plane (14±6°), pelvic hitch (5±2°), and rotation in the transverse plane (7±2°). In a younger population (n=18: 14 men & 4 women, aged 25-37 years) Dujardin et al (1995) showed that pelvic rotation (transverse plane) varied from 1.5 to 15° and from 1.5 to 9° in the coronal plane, which are both greater than in the older aged group. Three patterns of pelvic rotation at the beginning of stance phase (double support) were noted: Type I (most common) the pelvis was level in the transverse plane then rotated, Type II maximal rotation occurs and Type III minimal rotation with only 1.5-3.5° of motion. There appears to

Table 4.7 Range and SD of lumbar spine and pelvis motion in normals during walking

Author	Subjects Number (age (yrs))	Sagittal Plane F/E (°)	Frontal Plane LF (°)	Horizontal Plane Rot. (°)
Over ground				
Murray et al (1964)	60 M (20- 65)	P 3		P 10(3.5)
Murray et al (1967)	30 F (20-70)	P 5(1)		P 9.5(1)
Murray et al (1969)	64 M (20-87)	P 9 (74-80yrs) P 8 (81-87 yrs)		
Thurston et al (1981)	22 (M) (16-74)	P 4.0 (2.3-5.7) L 5.1 (3.5-8.1)	P 7.7(4.9-14.4) L 9.3(5.3-14.0)	P11.2 (5.6-19.1) L 8.3 (5.6-13.2)
Thurston & Harris(1983)	48 (M) (16-74)	P 4.1 (1.0) L 5.2 (1.2)	P 7.0 (1.9) L 8.5 (2.1)	P 10.1 (3.4) L 8.3 (2.0)
Judge et al (1995)	262626 (79 ± 6)	P 14 (6)	P 5 (2)	P 7 (2)
Taylor et al (1996)	16:10F,6M (20.47)	P 4.32 (1.68) L 3.24 (0.95)	P 11.69 (2.4) L 12.48 (3.0)	P 8.50 (2.10) L 6.44 (1.4)
Crosbie & Vachalathiti (1997)	108:50M,58F (20-82)	P 4.6 (0.3) H 38.4 (0.5)	P 6.9 (0.3)	P4.3 (0.2)
Crosbie et al (1997a)	108:50M,58F (20-82)	P 3.5 (1.5) L 3.5 (2.0)	P 6.0 (2.5) L 9.0 (3.5)	P 4.0 (2.5) L 4.5 (2.0)
Crosbie et al (1997b)	43: 20M,23F (50-82)	P 3.25 (1.75) L 3.5 (1.5) H 43.5 (5.25)	P 5.75 (1.75) L 8.25 (3.0)	P 3.25 (1.75) L 4.25 (1.75)
Whittle, Levine, Burke (1998)	21 M (21-39)	Lordosis range 23.4-22	L -0.7 (range -4.2 to 2.8)	L 0.4 (range -4.2 to 3.4)
Whittle, Levine, (1999)	20 (21-39)	P 2.79 (0.76) L 3.98 (1.21)	P 7.72 (2.26) L 7.55 (1.65)	P 10.40 (3.22) L 8.34 (2.19)
Callaghan et al (1999)	5 (M) (25 ± 2.8)	L 6.21	L 6.67	L 7.07
Treadmill				
Stokes et al (1989)	8: 3F, 5M No age given	P3.9 (0.5)	P8.3 (2.3)	P 7.9 (1.5)
Taylor et al (1999)	14: 9F,5M (20.6±2.8)	P 4.14 (2.53) L 3.83 (1.56)	P 11.5 (3.19) L 11.98 (1.86)	P 9.31 (3.55) L 6.39 (1.86)

Key: M-male, F-female, yrs-years, P-pelvis, L-lumbar spine, H-Hip; All movement values are mean with (standard deviations or ranges). F/E: Flexion/ Extension, LF: Lateral Flexion, Rot: Rotation be greater variability in pelvic position and degree of motion in younger people than in older. Kerrigan et al (1998) compared anterior pelvic tilt in a group of young and older healthy adults (n= 31 per group aged 18 -36yrs and 65 – 84 yrs) finding that there were significant differences (p<0.001) between the ages.

In the largest study of the hip and pelvis during gait in normal adults (108 participants, aged 20–82 yrs) Crosbie & Vachalathiti (1997) explored the correlation of hip and pelvic motion (values for pelvic range of motion are given in Table 4.7). Multiple regression analysis showed that in male pelvic tilt and pelvic list associated more with step length than in females, but in females step length makes a significant contribution to change in hip flexion range than in males (Crosbie & Vachalathiti, 1997). Looking at phase relationship these authors showed that vertical pelvic displacement leads anterior/ posterior pelvic movement which in turn leads pelvic hitch and lateral displacement. Phase 'locking' between hip flexion and anterior/ posterior pelvic motion was observed which may indicate a synchronised control mechanism thus suggesting more complex biomechanical determinants of walking than had previously been described (Crosbie & Vachalathiti, 1997).

Menz et al (2003) explored the acceleration patterns of the pelvis during level walking in 30 normals aged 22-39 years. The greatest acceleration was in the vertical direction with the pelvis accelerating vertically in a biphasic pattern with rapid upward acceleration at heel strike which lasts for 10% of the gait cycle which then descends. Prior to heel strike the pelvis accelerates forward which is rapidly halted by heel strike with a posterior acceleration and until foot flat the pelvis accelerates anteriorly again. The pelvis then accelerates vertically but from late midstance to toe off it moves downwards with a concomitant rapid posterior acceleration. After toe off, there is another gradual upward and anterior acceleration through early swing which then moves downwards at late swing for heel strike. There is minimal medial/lateral acceleration through the gait cycle except for a rapid acceleration to the contralateral side after heel strike which reverses until midstance. Between mid stance and the contralateral heel strike there is no constant pattern of acceleration. Although this research was undertaken on a younger population there is no reason to suspect that this pattern should change with age (Menz et al, 2003).

Pelvic motion may be a different between genders during gait if the results of Murray et al (1964) and Murray et al (1970) are considered. In the study of 60 men aged 20 – 65 yrs pelvic axial rotation was 10±3.5° and pelvic tilt had a mean excursion of 3°, at a set rate of 112 steps per minute. In a comparable sample of 30 women aged 20 -70 yrs Murray et al (1970) reported a mean of 9.5±1° pelvic rotation and 5±1° for pelvic tilt at a free walking speed of 1.3 ±0.15m/sec. Women appeared to have more pelvic rotation but less pelvic tilt than men of a similar age. In an older age group of men (67 – 87 yrs) however Murray et al (1969) report that pelvic rotation decreases with age from an average of 9.8° from 20 – 65 years to 8.4° in the 67-87 yr group, although though not a large decrease the average between 67-87 years is considerably less than that at 60 -65 years (13°). There is limited published literature regarding the range of movement of the lumbar spine and pelvis during walking. A review of the range of pelvic and lumbar spine movement described through the gait cycle is presented in Table 4.7 (p89A).

4.4.1.2 Lumbar Spine

Thurston et al (1981) showed that each movement of the spine was within 2° of the corresponding movements of the pelvis with frontal plane movements of the pelvis being the least variable in a group of 22 men (no age given). Axial rotation of the pelvis was virtually constant for each subject but was affected by variations in cadence and step length. In a later study by Thurston and Harris (1983) stated that "*a greater variability was shown in movement of the lumbar spine compared to pelvic movement from subject to subject*". Using a population of 48 males (mean age 32.3yrs, 16 – 74 yrs) the angular displacements of both the pelvis (4.1±1.0°) and spine (5.2±1.2°) in the sagittal plane ($p<0.02$), and the angular displacements of the spine in transverse plane (8.3±2.0°) decreased significantly ($p<0.05$) with age.

To investigate the reliability of data between the normal speed and slow speed walking group, Taylor and co-workers (1999) assessed lumbar spine angles during

Table 4.8: Mean lumbar spine motion during walking for senior (aged from 50 – 82 yrs) male and female subjects (n=43 (23 females and 20 males)) (Crosbie et al, 1997b).

Group	Speed	LF (°) Mean (SD)	F/E (°) Mean (SD)	AR (°) Mean (SD)
Female	Preferred	7.5 (3.0)	3.5 (2.5)	4.0 (2.0)
Male	Preferred	9.0 (3.0)	3.0 (1.5)	4.5 (1.5)
Female	Fast	9.5 (4.5)*	4.0 (2.0)	3.5 (1.0)
Male	Fast	13.0 (4.5)*	4.0 (2.5)	5.0 (2.0)

Key: LF lateral flexion, F/E flexion/extension, AR axial rotation,
* significant ($p<0.01$);

treadmill walking. Consistent measurement of the angular movements of the lumbar spine and pelvis could be taken in four-minute test length of treadmill walking and there was no significant change in the mean amplitude of the lumbar spine and pelvis during slow and normal walking.

Crosbie et al (1997a) looked at the patterns of whole spinal motion during free walking. Lower thoracic, lumbar spinal segments and the pelvis were assessed for walking at a self-selected speed in healthy adults from age of 20 – 82 yrs. Motion of the lumbar spine was defined as the relative motion of the lower trunk segment with respect to the pelvic segment. Peak to peak range of motion for lateral flexion of lumbar spine was 9.0 ±3.5°. This indicated that the lumbar segment was displaced more than the pelvis and lower thoracic part, 6.0±2.5° and 7.0±3.0°, respectively. The patterns of movement in the lumbar spine complemented those of the pelvis.

Sartor et al (1999) assessed trunk movement in 17 healthy people) age 20-59 yrs) finding a mean sagittal plane range of 5-7° of extension, 6° of lateral lean firstly to the stance leg and then 6° to non stance leg and 13°of rotation.

These results suggest that the spinal movements associated with walking were linked to the primary motions of the pelvis and the lower limbs. Whittle et al (1998) agreed with this pattern of 3-dimensional motion but the values for the range of movement were less (Table 4.7, p89A), than those for Crosbie et al. Using the same subjects, Crosbie et al (1997b) showed that there is an increased range of motion in each segment with increased walking speed. This was particularly so for lateral flexion, with more gender-related differences in pattern and range of motion compared to the other planes of motion (Table 4.8). Crosbie et al (1997b) agreed with the results of Thurston and Harris (1983) who reported a significant reduction in spinal range of motion with advancing age during walking.

Table 4.8 shows that the gender effects on lumbar spine motion during walking were minimal, with non-significant differences for all movements at the preferred speed.

Table 4.9 Lumbar lordosis and pelvic tilt in walking and standing (°), (Whittle and Levine, 1995).

Walking	Lumbar Lordosis	Pelvic Tilt (Anterior/Posterior)
Centre	28.0 (6.1)	10.5 (4.4)
Max	2.1 (0.7)	1.4 (0.4)
Min	- 2.0 (0.7)	-1.5 (0.5)
Range	4.2 (1.2)	2.9 (0.9)
Standing	**Lumbar Lordosis**	**Pelvic Tilt (Anterior/Posterior)**
Normal Stand	32.5 (6.9)	11.8(4.4)
In Anterior Tilt	42 (7.0)	23.0(4.8)
In Posterior Tilt	22.6(8.9)	3.2(5.5)

Key: mean (SD), all results in degrees,

28 female subjects, average 23.4 years; Lordosis defined as the sagittal plane angle between the two base plates at T12 and L1.

22 females were also measured in maximal anterior and posterior tilt in standing. (results in blue)

The only significant difference at the fast speed was for lateral flexion significant (F=11.3; p<0.01).

There were significant differences between the data for younger and senior subjects for range of motion in all segments and about most axes. The authors did not give any explanation whether the reduction in range of motion was associated with age affects or walking speed effects. Senior subjects walked more slowly in both conditions (preferred and fast) in comparison to younger subjects; further supporting the overall reduction in lumbar spine movement with age during walking.
In contrast Twomey and Taylor (1983) suggested that there is no particular reason to believe that age leads to reduction in the available spinal motion required for walking. Their research indicated that the natural range of the lumbar and lower thoracic spine is considerably greater than would be necessary for the movements during walking, however this study was undertaken on cadavers. This would indicate that the older population tend to reduce movement voluntarily during walking to gain more central control and balance.

In a recent study in 1999, Callaghan and colleagues examined the effect on the lumbar spine motion of three different walking cadence (normal, slow, and fast) and two different arm swing conditions (free and restricted arm swing). Results of lumbar kinematics demonstrated increased peak to peak range of lumbar motion with increased cadence. The lumbar spine became more flexed with increased walking cadence. At slower walking speeds there was less flexion-extension range of motion as well as less lateral bend and axial rotation. Restricted arm swing during gait decreased both the axial rotation and lateral bend of spine motion, particularly at the normal and fast walking cadence, while there was no significant difference in slow cadence. During slow walking the amplitude of the arm swing is usually small. Interestingly, flexion/extension range of lumbar motion was not altered by the lack of arm swing during walking. This appeared to contradict the findings from Elftman (1939) that arm swing reduced axial rotation. One benefit of arm swing during gait was a reduction of trunk muscle activation level (Callaghan, et al., 1999) and this could support the theory of Elftman (1939) that the arm swing help to control rotation. However this study was undertaken on a younger population so results cannot be directly transferred to elders.

Whittle and Levine (1995) reported measurement of the lumbar lordosis in walking, using a method based on the angle of skin surface at the upper (T_{12}-L_1) and lower ends (between PSIS) of the lordotic curve (Table 4.9). Their results showed that the mean lordosis in walking was 28°, 4.5° less than in the standing position. In contrast, the mean pelvic tilt decreased 1.3° between walking (10.5±4.4°) and standing, (11.8±4.4°), suggesting that the average trunk position is inclined further forward during walking than in standing. The pattern of oscillation of lumbar lordosis was consistent for repeated readings on one individual, however it varied between subjects. The majority of people showed increased lordosis shortly after heel strike, while at mid stance the lordosis was generally reduced, although many showed a second peak of increased lordosis, which was superimposed on this decrease.

There is some evidence that walking on a treadmill increases the amplitude of lumbar spine (Taylor et al, 1999) but not pelvic motion during walking (Stokes et al, 1989) (Table 4.7, p89A) but both of these studies were undertaken on a small number of participants in a young age group.

In a pilot study, Bastian et al (1991) tested the hypothesis that lumbar lateral flexion (LF) and pelvic rotation (PR) are coupled motions during gait. This correlation depends on the degree of lumbar flexion/extension therefore the delay between LF and PR motion is purported to be because of ligamentous elongation in the lumbo-pelvic region. These researchers tested three normal adults and the results supported the idea that coupled motion is sensitive to the degree of lumbar flexion and extension, and thus LF and PR correlated more closely when the lumbar spine was extended or in a mid-range position. Correlation during lumbar flexion was low and consistently negative, but the results need to be viewed with caution as only three participants were involved.

All these findings are clinically important. They show that lumbar alignment and movement affects pelvic rotation, which is an important determinant of gait quality.

Table 4.10 Normal angles (°) and pattern for hip kinematics in sagittal plane during stance phases of gait

	Heel Strike (Initial Contact)	Loading response	Mid Stance	Terminal Stance	Pre Swing (Toe off)
% of gait cycle	0 -2	2 - 10	10 - 30	30 - 50	50 - 60
Hurwitz et al (1997)	22	20 to 10	10 to 0	0 to -10	-10 to 0
Krebs et al (1998) (Mid Angles only)	20	20	5	-5	5
Oatis (1990a) (Mid Angles only)	20 to 30	20 to 30	5	-10 to -15	5
Perry (1992)	30	30	30 to -5	-5 to -10	-10 to -5
Winter (1987) (Mid Angles only)	20	18	0	-10	-5
Pattern	Flex.	Flex.	Flex. To Ext.	Ext.	Ext. to neutral
Key: Flex. =flexion, Ext. =Extension, all angles in (°), -ve values indicate extension					

Table 4.11 Normal angles (°) and pattern for hip kinematics in sagittal plane during swing phases of gait

	Initial Swing	Mid Swing	Terminal Swing
% of gait cycle	60 - 73	73 - 87	87 - 100
Krebs et al (1998) (Mid Angles only)	10	15	22
Hurwitz et al (1997)	0 to 10	10 to 20	20 to 22
Perry (1992)	-5 to 20	20 to 30	30 to 35
Oatis (1990a) (Mid Angles only)	10	15 to 20	30
Winter (1987) (Mid Angles only)	0 to 5	10	20
Pattern	Ext. to Flex.	Flex.	Flex.
Key: Flex. =flexion, Ext. =Extension, all angles in (°),-ve values indicate extension			

In clinical terms this suggests that the restoration of lumbar alignment and movement are prerequisite for restoration of normal gait.

4.4.2 Hip

Hip kinematics and kinetics during normal walking have been explored by many researchers and have been well documented in many texts (e.g. Whittle 1996 a & b, Perry, 1992; Chao & Cahalan, 1990; Oatis, 1990a; Winter 1987, 1984, 1983). Krebs et al (1998) give a comprehensive overview of the biomechanics of the gait cycle (GC) giving kinematic, kinetic and muscle data in all planes for the whole cycle. Some of the first and most extensive studies on normal walking were undertaken by Murray et al (1964, 1967, 1969, 1970) and Finlay (1969) and although measurement techniques are more advanced the basic implications from this work still apply.

4.4.2.1 Kinematics during normal gait

Although there are variations in the numerical values, depending on the analysis technique, instrumentation or maker set used, the basic components of movement are very similar (Table 4. 10 - 4.13). One approach is to take the vertical thigh to represent the zero position in quiet standing (Murray et al, 1964; Kadaba et al, 1989; Perry, 1992), if this is so then the sagittal range of motion at the hip during gait is from 30° flexion to 10° extension. Some researchers observe the range of motion of the thigh, rather than the interaction of the femur and pelvis. This gives greater values in extension than hip motion alone but smaller values in flexion (22° flexion to 20° extension) (Perry, 1992).

The hip rotates through approximately 40° of movement in the sagittal plane during the average normal stride (Perry, 1992; Chao & Cahalan, 1990, Kadaba et al, 1990). The hip flexes to 30-35° in late swing at 85% of the GC, and reaches maximum hip extension (10° from vertical) at toe-off (50% of the GC) (Perry, 1992; Chao & Cahalan, 1990; Oatis, 1990a) (Table 4.10 & 4.11). Murray (1967) indicated that maximal hip extension occurred with maximal anterior pelvic tilt. Judge et al (1995)

Table 4.12 Pattern of hip kinematics in frontal and transverse planes during stance phases of gait (Oatis, 1990a; Perry, 1992)

	Initial Contact	Loading response	Mid Stance	Terminal Stance	Pre Swing
% of gait cycle	0 -2	2 - 10	10 – 30	30 - 50	50 - 60
Pattern (frontal plane)	Add (10°)	Add (5°)	Less add	Less add/ neutral	neutral
Pattern (transverse plane)	Slight Lat Rot or neutral	Max Med. Rot.	Med. Rot.	Med. Rot./ neutral	Max Lat. Rot.
Key: Abd =Abduction, Add =Adduction Lat. Rot. =Lateral rotation, Med. Rot. =Medial rotation					

Table 4.13 Pattern of hip kinematics in frontal and transverse planes during swing phases of gait (Oatis, 1990a; Perry, 1992)

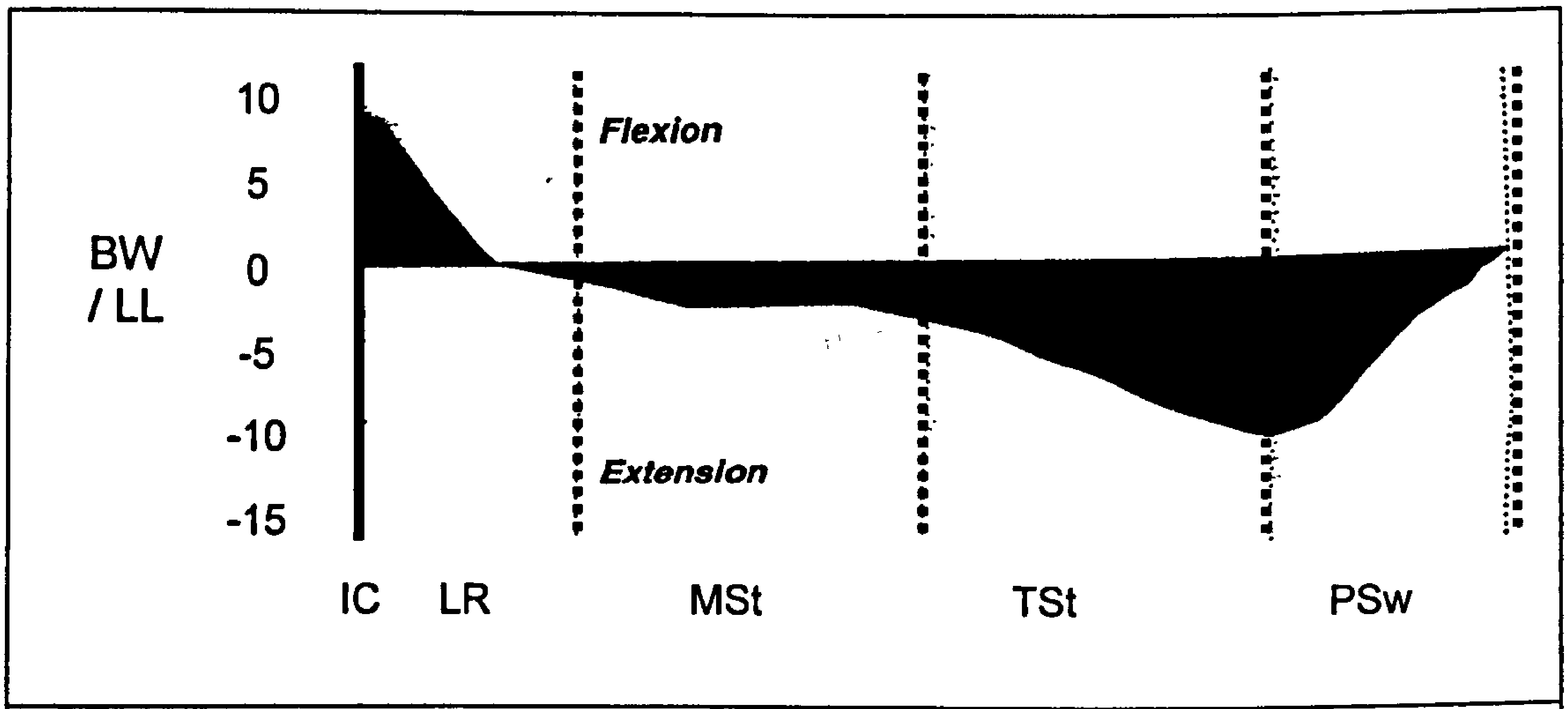
	Initial Swing	Mid Swing	Terminal Swing
% of gait cycle	60 – 73	73 – 87	87 - 100
Pattern (frontal plane)	Slight abd.	Neutral	Slight abd./ neutral
Pattern (transverse plane)	Lat. Rot.	Lat. Rot.	neutral
Key: Abd =Abduction, Add =Adduction Lat. Rot. =Lateral rotation, Med. Rot. =Medial rotation			

showed peak hip extension in terminal stance in 26 older adults (79±6yrs) to be -8±7° in comparison to -11±7° in a younger (26±6yrs).

Goniometry attachment is more cumbersome and may produce more movement/ 'slippage' hence greater error (Johnston & Smidt, 1969). The instrument of measurement may also appear to alter the degree of motion Johnston & Smidt (1969) used an electrogoniometer to assess hip movement during gait showing a range of 37±5.4° flexion and 15±5.6° of extension through the gait cycle.

Frontal plane motion during gait (Abd/ Adduction) gives a total transverse movement of 8° (Perry, 1992, Oatis, 1990a) at around 40% of the GC (Chao & Cahalan, 1990; Oatis, 1990a) with a smaller degree (5-7°) occurring during early swing phase (Perry, 1992) (Table 4.12, 4.13). These researchers also reported a 4-5° movement in both medial and lateral rotation of the hip joint through the swing phase of the gait cycle (Perry, 1992) (Table 4.13). These results agree with Johnston & Smidt (1969) who indicated a mean of 7±3.1° of abduction and 5±1.9° of adduction through the gait cycle. However Johnston & Smidt recorded a larger degree of rotation (4±3.1° of medial rotation and 9±4° lateral rotation) which may be due to slippage of the electrogoniometer.

Crowinshield et al (1978a) and Winter et al (1990) both showed that hip flexion range during gait declines by 10 – 15° with age, which helps to decrease both step length and walking velocity. Likewise Kerrigan et al (2001a) reported a reduction in hip extension range during walking in elderly adults (14.3±4.4°) compared to 20.4±4.0° in a younger age group, probably due to flexor or anterior capsule tightness. It is unclear from current research if the reduced sagittal plane joint excursion is responsible for the reduction in walking velocity or vice versa, Oatis (1990a) suggests that change in joint excursion cannot occur without alteration in walking velocity or general alterations to walking ability. In contrast Kerrigan et al (1998) report minimal differences between young (18-36 yrs) and old (65 – 84yrs) for peak hip kinematic values at a comfortable walking speed.



Key: IC Initial Contact (Heel Strike), LR Loading Response, MSt Mid Stance,
TSt Terminal Stance, PSw Pre Swing (Toe off) BW/ LL = Body weight/ leg length

Figure 4.7 Sagittal plane hip torques during normal walking (Perry, 1992, p115)

Table 4.14 Peak external hip moments during gait in 19 healthy elderly (Hurwitz et al, 1997)

Movement	External Moment - Mean (SD) % Body weight * height	Point in Gait Cycle
Extension	2.9 (1.5)	Late stance
Flexion	4.5 (1.4)	Early Stance
Abduction	0.9 (0.7)	Very early stance
Adduction	5.1 (1.0)	Early to late stance
Lateral Rotation	0.7 (0.4)	
Medial Rotation	0.8 (0.4)	

Murray et al (1964) and Murray et al (1970) describe differences in hip and pelvic ranges between men and women during gait (reduced flexion and extension excursion, and transverse rotation of the pelvis) which these authors predict cause a shorter step and stride lengths and resultant faster cadence in females. Women also have less vertical displacement during walking as a result of the short step length.

4.4.2.2 Kinetics during normal gait

The patterns of hip joint kinetics through the gait cycle are usually represented by the sagittal and frontal plane as these planes demonstrate the greatest forces/ moments. There is little reported evidence on the transverse plane moments as they are regarded as negligible. The predominant internal moment in the sagittal plane is extension and in the frontal plane, abduction.

Sagittal Plane

The ground reaction vector at the hip joint moves posteriorly through the stance phase from an anterior position at loading response. The initial internal moment of force is flexion (6.9 BW/LL units) (Perry, 1992) but as the vector moves posteriorly through loading response the moment of force changes from neutral to extension. Extension moment gradually increases from 2.3 BW/LL units at the start of mid stance to the maximal value of 10 BW/LL units at the end of terminal stance (49% of GC) (Perry, 1992) (Figure 4.7). Peak flexion torque occurs at initial contact and peak extension torque at start of pre-swing (Krebs et al, 1998). Hurwitz et al (1997) reported peak external hip moments during gait in 19 healthy elderly (age 61 ± 8 yrs) and 19 with unilateral hip pathology (age 60 ± 8 yrs). Using inverse dynamics they calculated the hip moments as the percentage of body weight multiplied by height (Table 4.14). Therefore the results cannot be directly compared with those of Perry (1992), but the patterns of torques are comparable.

The results of joint kinetics during gait in 40 healthy adults (age 18–40 years) from Kadaba et al (1989, 1990) indicate similar patterns of moments to those of Hurwitz et al (1997), although Kadaba et al used bodyweight*leg length to calculate the moments compared to body weight*height of Hurwitz et al. The results from these studies cannot be compared directly as Kadaba et al (1989) do not report values. Kadaba et al (1989) looked at the repeatability of gait parameters over 3 walking trials on one day, and over 3 days showing excellent repeatability for hip 0.98-0.99 flexion/extension, 0.88-0.96 for ab/adduction for repeated tests within a day and between days and 0.89 for hip rotation on a single day. Hip rotation between days had poor reliability of 0.41–0.48. Repeatability of pelvic measures was good for the frontal and horizontal planes for both tests (0.72–0.96) but was poor for sagittal plane motion both within and between days (0.24– 0.67).

Winter (1984) combines data from several studies to give a complete overview of the kinematics and kinetics of gait. The hip moment pattern in the line of progression shows the classic external extensor motor pattern (peak 0.6Nm/kg, within first 5% GC) for the first half of the stance phase and then the change to a external flexor moment (peak -0.4 Nm/kg, at 50% GC) which continues into swing phase, before a 2nd extensor peak occurs (0.2 Nm/kg) at 90%GC. However when looking at repeated trials the hip moment shows high variability (CV=72%) but Winter hypothesises that this is due to the high number of biarticular muscles across the hip joint. The muscle moments for each of the joints change in magnitude with a corresponding change to walking velocity with the basic patterns remaining the same. Conversely Kirkwood et al (1999b) report maximal sagittal plane hip moments in 30 healthy older participants (65.4±6.02 years) during level walking to be -0.89 Nm/Kg, which is considerably larger than the results of Winter.

Force data from older people are reported by Stansfield & Nicol (1998))40-60 year olds: mean 63 yrs) for walking on flat, up and down ramps, camber, ascending and descending stairs, indicating that there was a 30% increase in force during walking and a 15% increase for stair negotiation compared to studies involving older subjects.

Frontal Plane

At heel strike the frontal plane vector lies laterally (Abduction) but moves medially (Adduction) immediately the limb is loaded in loading response. The vector remains medial through out the stance phase (Perry, 1992). Consequently during single support gravity pulls the body centre of mass downward (contralateral pelvic drop). An internal hip abductor moment counters this effect and supports the pelvis and upper body (ipsilateral side) during single support.

Paul (1967, 1971) first calculated reaction forces on the femoral head in healthy men and women during gait using Newtonian mechanics and found that the force peaks twice, once after initial contact and the second before pre-swing. The former ranging from 250 – 400% (BW), whilst the latter ranged from 400 -700% (BW) with the values for men being higher than those of women..

It is difficult to directly compare data from different studies on hip kinematics because each uses different units of measurement and walking velocity. It should be noted however that the pattern of double contact peak, 1st at early and 2nd at late stance phase, described by Bergmann et al (1993, 2001) remains the same irrespective of the analysis method or walking velocity. The average healthy person loads their hip joint up to 238% (BW) during walking at 4km/h with a peak of 248% (BW) (Bergmann et al, 2001). In the present study contact forces are not presented.

Long et al (1993) reported vertical and fore and aft forces (%BW) in 18 patients (age 55 (range 35 -85yrs)) at two years post uncemented THR. The vertical load for these patients was 131% at one year post operation and 123% of BW at 2 years. A difference of 8% at one year and 12% at two years compared to the data from the uninvolved leg. These patients are not totally comparable with those with a group of people with a cemented THR as they are younger and fitter and no walking velocity has been given, the data however is useful to give an indication of walking ability.

4.5 HIP, PELVIS AND LUMBAR SPINE KINEMATICS AND KINETICS DURING GAIT IN THOSE WITH HIP PATHOLOGY OR TOTAL HIP REPLACEMENT

Although there is a vast array of published literature on the hip following hip replacement few papers give details of both mean range and motion patterns, however a summary of hip data will be given in section 4.5.3. Pelvic motion in

Table 4.15 Mean pelvic and spine movement in those with OA hip during walking (Thurston, 1985)

	OA Group Mean (SD) (°)	Controls Mean (SD) (°)	Mean diff (°)
Pelvis			
Sagittal Plane	8.6 (4.41)	4.3 (1.20)	4.3*
Frontal Plane	4.0 (1.02)	5.7 (0.70)	-1.7**
Transverse Plane	9.2 (3.85)	10.1 (4.17)	-0.9
Spine			
Sagittal Plane	5.2 (2.25)	5.2 (1.07)	0
Frontal Plane	7.2 (3.76)	6.8 (1.81)	0.3
Transverse Plane	7.7 (2.31)	8.8 (2.49)	-1.1
Key: * Significant at p<0.005 unpaired t-test ** Significant at p<0.01 unpaired t-test			

walking after a hip replacement has only been reported by a few authors e.g. Bennett et al (2006) or Whatling et al (2006). Bennett et al (2006) report a mean range of 5.9° in eight patients (age 60.8±5.8 yrs) at 6 weeks post total hip replacement, whilst Whatling et al (2006) report three-dimensional pelvic motion during gait in 10 patients after hip replacement with mean planar range of 3.15±1.21° (sagittal), 5.08±1.98° (frontal) and 13.04±°2.97 (horizontal). Direct comparison cannot be made as no age or time since surgery has been reported by Whatling et al. but it is likely that the data from Whatling was recorded more than 6 weeks after surgery. Mean sagittal plane data are smaller in range than that reported by Thurston (1985), (8.6 ±4.41°) who assessed pelvic movement in those with OA hip but Bennett's data are larger than the range from Thurston's age matched controls (4.3 ±1.20°) Table 4.15.

To date there have been only two published research studies of lumbar spine movement during walking in people with total hip replacements. Both of these have only reported lateral spinal movement. Therefore this section will focus on the evidence regarding lumbar movement during walking in people with OA hip and then discuss hip kinematics in those after THR. Murray (1967) in a case study reports temporal changes to the gait of someone with a painful OA hip. With a slower walking velocity compared to normal, the participant spent 59% of the gait cycle on the affected limb in stance compared to 80% on the sound side. The participant reduced the stance time on the affected side to decrease painful weight bearing with a consequential increase in swing time to try to step forward with the painful side. The step length was shorter on the affected side by 10cm (41, good limb to 31cm, affected limb) and considerably reduced compared to the norm (78cm).

4.5.1. Lumbar spine motion during walking in those with OA Hip

A number of gait abnormalities involve an abnormal pelvic tilt and a compensatory change in the position of the lumbar lordosis. The lumbar spine is subjected to abnormal and potentially harmful stresses during gait in patients with lower limb disabilities (Oatis, 1990a). Murray et al (1971) were the first authors to explore gait in OA patients using photography and the results they found are comparable with those using the more advanced technology of today.

Thurston (1985) is the main author to observe pelvic and lumbar spine movement in people with an osteoarthritic hip during walking and to compare the findings to those with no arthritic changes. He hypothesised that the exaggerated spinal movements associated with a painful gait pattern from OA may be the main contributor to low back pain (LBP). Patients with osteoarthrosis of the hip have abnormal movement of the spine in performing the exaggerated movements associated with the painful gait (Thurston, 1985).

Using a television/computer system, Thurston assessed 19 male patients with X-ray evidence of OA awaiting total hip replacement (age 65.1±7.77 yrs). Ten aged matched (mean 63.4±8.06yrs) males with no evidence of OA were also assessed. 12 of the patients with OA had LBP and of these five people had alteration in the static pelvic position in standing. Overall the pelvic and lumbar spine movement in the OA group retained the same pattern as the normal group but the specific values differed significantly in places. In those with more severe OA both sagittal plane pelvic and lateral spinal movement showed the greatest increases. The results (Table 4.15) showed significant differences in ROM between the groups in movement of the pelvis in the sagittal and frontal plane (8.6° vs 4.3° ($p<0.01$), 4.0° vs 5.7° ($p<0.001$), respectively). Increased sagittal plane movement of the pelvis showed a positive correlation with sagittal plane ($p<0.005$) and frontal plane ($p<0.001$) movement of the lumbar spine, implying that movements of the pelvis and lumbar spine are reciprocal and that a large component of lumbar spine motion results from pelvic motion during gait. Hip flexion contracture or reduction in sagittal plane hip movement was compensated by an increase in sagittal plane movement of the pelvis, suggesting that the degree of loss of lumbar spine movement can be used as a measure of severity (Thurston, 1985).

This was ratified by Lee et al (1997) who showed a positive significant correlation between anterior pelvic tilt during gait and limited extension (Thomas Test) ($r=0.60$, p<0.0001) in 82 hips with flexion contracture. Regression analysis showed that peak hip extension during walking, peak knee flexion and step length all significantly predicted peak anterior pelvic tilt angle. The Thomas test was not a good predictor of peak anterior title angle showing that the results of this static test cannot be extrapolated to the dynamic measurement during gait. Shimada (1996) suggested that hip flexion contracture could not be compensated by pelvic tilt and exaggerated lumbar lordosis when: hip flexion contracture >15°, bilateral contractures present, associated knee flexion contracture present and ambulatory dysfunction. Lee et al (1997) indicated that knee flexion is a compensation for hip flexion contracture so the magnitude of hip flexion contracture may dictate the patterning of compensation. The pattern of pelvic motion in relationship to lumbar spine motion was variable. Some patients showed increased movements while others showed decreased movements; this was most obvious in the frontal plane. It was concluded that the more severe the disease, the greater the increase in frontal plane movement of the pelvis resulting in greater spinal movement in the sagittal and frontal planes.

The main points of note from the pattern findings of Thurston (1985) were: that during stance phase of the affected leg, anterior pelvic tilt increased and the gross movement imposed by the painful hip caused loss of the normal contribution of the unaffected leg to the movement of the pelvis. The sagittal plane movement of the lumbar spine was less consistent; in some patients the lumbar spine moved very little but was reciprocal with the pelvis, while in other patients, this was not so. In the frontal plane, movement of the pelvis retained the features of two major deflections, while the neutral position of the pelvis in the frontal plane varied according to the degree of abduction or adduction contracture of the hip. The pattern of two major deflections was lost in more severely affected patients, and was replaced by a single peak trough pattern - single deflection.

In the transverse plane, the pelvis and spine in the patient group produced relatively consistent patterns - a single peak trough plot, while in the control group the dichotic notch was seen. Transverse plane patterns fell into opposite groups either displaying limited pelvic movement or a sudden twist of the lumbar spine during swing phase of the affected leg. The timing of these events changed. This appeared to correlate with the incidence of low back pain but the finding needs further research as numbers in this study were small and the relationship was not significant (Thurston, 1985).

The association of osteoarthrosis of the hip and LBP has been recognised by clinicians but it is unknown which came first, or if one caused the other. Thurston (1985) reported interesting results about the timing of the movements of the pelvis in the transverse plane. In all patients with LBP history a single peak trough plot occurred after the position of the second expected notch-V shaped wave, whereas in those patients without LBP history, these events occurred before the expected position of the notch. The results of Murray et al (1971) show similar trends those of Thurston (1985) but the equipment used by Thurston was more advanced and comparable with the Motion Analysis Systems used today.

Rowe and White (1996) investigated lumbar spine motion during walking in a group of 10 nurses following one or more episodes of LBP. The group mean active range of side flexion varied from 1.8° to -2.2° ±0.26° for axial rotation from 3.7° to -2.9°, (±0.41°) and for forward flexion from 6.1° to 3.8° ±0.61°.

Their results indicated that nurses who had previously experienced one or more episodes of LBP showed little or no residual effects in their gait. Also their temporal parameters of gait were unaffected by previous back pain. The angular kinematic data indicated a regular, symmetric and reciprocal pattern of lumbar spine motion in all three degrees of freedom, axial rotation, lateral flexion and forward flexion. Thus for this population, spinal problems appear not to alter the gait pattern significantly.

A clinically relevant feature, reinforced by Rowe and White (1996), is the relationship between axial rotation and side flexion data during walking. It has been debated for a number of years, whether axial rotation in the lumbar spine during walking is coupled with ipsilateral or contralateral side flexion. The data from this study indicates that axial rotation is coupled with contralateral side flexion. It is suggested that this occurs in order to keep the trunk facing forwards, while simultaneously shifting the centre of gravity of the upper body over the supporting leg and so reducing the joint movements and rotation of the pelvis to give a longer step length.

Hurwitz et al (1997) looked at gait compensations in 19 patients (average age 60±8yrs), who had moderate to severe unilateral OA of the hip, and their relationship to pain and passive hip motion. They showed that these patients walked with a decreased dynamic flexion/ extension of the hip (17±4°) and with a hesitation or reversal in the direction of sagittal plane motion as they extended the hip. This alteration in the pattern of motion was interpreted as a mechanism to increase effective extension of the hip during stance through increased anterior pelvic tilt and lumbar lordosis. Thus, one possible mechanism to compensate for inadequate extension of the hip would be to increase lumbar lordosis and flex the pelvis forward, although pelvic and lumbar motion were not measured by these researchers. This interpretation is consistent with the study of Murray et al (1971) and Thurston (1985) who measured an increase in anterior-posterior pelvic tilt from increased lumbar flexion-extension and identified it as a compensation strategy for the limited range of motion of the hip during gait. Patients who have osteoarthrosis of the hip may compensate for a lack of extension by altering the motion of other joints.

Increased pelvic and spinal excursions compensate for loss of range of motion of the hip, may contribute to back pain among subjects who have osteoarthrosis of the hip (Watelain et al, 2001). Excessive lumbar and pelvis motion, in the presence of insufficient hip motion, restores normal pattern of bending forward and gait (Gore et al, 1975). Sahrmann (1987) suggests that excessive lumbar mobility leads to tissue overloading, microtrauma and ultimately to development of degenerative joint and disc disease. This statement is supported by Oatis who indicated that:

> "*Limited hip motion can be compensated for by increased pelvic motion. However the price for this compensation is excessive lumbar spine motion during locomotion, which could contribute to low back pain*" (Oatis, 1990a, p170).

It can be hypothesised that restoring normal hip and lumbar spine mobility after THR would eliminate the need for increased pelvic and lumbar motion, reducing lumbosacral stresses.

Even with a minimal level of radiographic evidence of OA and from observation of functional limitations Watelain et al (2001) found that 17 people with early OA hip had a slower walking speed (12.4%), and reduced stride length (6.45%) compared to 17 people with no history of OA. Pelvic movement in the OA group was 2.5 times more upwardly tilted at push-off and pelvic obliquity increased (dropped) more than 2.4 times on the unsupported limb at push-off. The OA group had a greater range of pelvic movement through the gait cycle: tilt 111.72%, obliquity 36%, and rotation 0.89%. Therefore the OA group compensated for their reduced hip range by increasing their sagittal pelvic movement thus allowing effective hip extension at push off and modifying the stride length resulting from limited hip movement. Increased pelvic obliquity is seen when the weight bearing hip is painful or when the hip abductors are weak. If the weight bearing hip is painful, patients will reduce abductor activity thus increasing pelvic obliquity and trunk side flexion to shorten the moment arm between the hip and the centre of mass of the upper body, reducing the load across the hip joint (Watelain et al, 2001).

Overall lumbar spine and pelvic movement during walking are exaggerated to compensate for the limitations to hip joint movement because of OA.

4.5.2 Lateral lumbar spine movement during walking post total hip replacement

Lateral spinal movement in those with THR has been researched by two groups Vogt et al (2003a) and Perron et al (2000). Perron et al assessed hip function and lateral displacement of the trunk and pelvis in 18 people (65.5±6.5 years) at nearly 1 year post total hip replacement with a control group of 15 healthy adults aged 65.6±6 years. Although the main study researched the hip post THR, Perron et al reported mean lateral manubrium displacement range over the first step to be 50% larger in those with

Table 4.16 Summary of walking velocity after THR

Authors	Sample size (no. of THR)	Age (yrs)	Time post op (mths=months, yr =years)	Velocity (m/s) unless stated
Ajemian et al (1997)	8	64± 2	4 mths 8 mths	1±0.04 1.08±0.03
Berman et al (1991)	41		8 12 18mths	0.86±0.18 0.88±0.13 0.96±0.16
Kyriazis & Rigas (2002)	25 20	51±5 52±4.5	1yr 8-10yrs	1.02±0.2 1.12±0.1
Loizeau et al (1995)	4	67.3±8	3.8±2.5 yr	0.748± 0.14
Madsen et al (2004)	10	63.6 ± 8	6 months	1.17±0.18
Olsson et al (1986)Paper 5	21	69	6mths 12 mths	1.07 1.16
Perron et al (2000)	18	65.6 (6.0)	12mths	1.07±0.2
Rowe et al (1989)	65	63±9 (SE)	12 post	
Stanic et al (1993)	56	61	12 mths	0.92±0.21
Stauffer et al (1974)	25	63	6 mths	0.62
Wall et al (1981)	16: 6M,10F		 6mths 12mths	Stat/s 0.59±0.17 0.58±0.14
Wykman & Olsson (1992)	65: 17M 33F	64	53 mths	1.13

a hip replacement with a larger linear acceleration of the manubrium marker through he gait cycle. These researchers also measured lateral pelvic displacement over the first step reporting no difference between the healthy and operated participants.

The study by Vogt et al (2003a) examined medio-lateral excursion of the trunk during walking on a treadmill in 12 males (61.5±6.7 years) at 3.5 – 6 weeks post hip replacement and compared the results to 10 healthy men (59.5±6.1 years) and 10 healthy younger men (30.4±3.4 years). Overall the range of medio-lateral displacement 5.6°, 5.2° and 4° for the hip replacement, older control and younger controls was not significantly different despite significant differences in walking speed (2.1m/s, 3.0m/s, 2.9m/s respectively). Two thirds of the hip replacement group, however, had a lateral lean to the operated side. This supported work by Mackinnon & Winter (1993) who suggested that lateral lean of the trunk may be present to reduce frontal plane moments.

Rotation of the sacrum was also measured in these participants showing significant ($p<0.05$) reductions in the hip replacement and elderly groups compared to the younger group. The results indicated that older people may have restricted pelvic and lumbar spine motion during walking confirming the suggestion by Crosbie et al (1997b).

4.5.3 Hip biomechanics during walking post total hip replacement

The main discussion in this section will be on the kinematics and kinetics of gait, temporal characteristics will not be discussed however gait velocity post THR is represented in the literature summary in Table 4.16 and joint movement during gait in Table 4.17 (p106A).

4.5.3.1 Kinematics

Skinner in 1993 published a review article on joint replacement outcomes, giving a clear indication that post THR the walking pattern did not necessarily return to normal. He proposed that the lack of return to normality was due to a combination of previous abnormal gait pattern, muscle weakness, reduced proprioception and prosthetic design (Skinner, 1993). From the single case study of Murray (1964) and

Table 4.17 Summary of hip movements during walking after THR

Authors	Sample size	Age	Time post op	Flexion (°)	Extension (°)	Frontal Plane (°)	Rotation Lateral (°)
Ajemian et al (1997)	8 THR	64± 2yrs	4 mths 8 mths	24.9±1.1 24.0±0.9	10.4±1.2 14.2± 1.4		
Aminian et al (2004)	8 THR	69±4	18-36 mths	38±4			
Bennett et al (2006)	8 THR	60.8±5.8	6 weeks	27.3		7.6	11.5
Long et al (1993)	18 THR	88 (35-85)	12 mths	37 (op) 41 (non op)			
Madsen et al (2004)	10 THA	63.6 ± 8	6 months	39.4± 5.3 Mid stance		87.3±3.9 Mid stance	
Olsson et al (1986)Paper 5	21 THR	69	6mths 12 mths	37 38			
Perron et al (2000)	18 THR	65.6 (6.0)	12mths	25		2.5-3	6 (range)
Rowe et al (1989)	65	63±9 (SE)	12 post	16.94			
Stanic et al (1993)	56	61	12 mths	27.18±8.37 (op) 32.79±10.25 (non-op)			
Stauffer et al (1974)	25 post THR	63 yrs	Not given	32.8		5.8	7.4 (range)
Whatling et al (2006)	10 THR	Not given	Not given	33.1±6.2		7.35±2.93	11.79±3.8

the first photography study in 1971 (Murray et al (1971), the changes in sagittal motion in walking with an OA hip are clearly explained. The pelvis has a larger degree of anterior tilt through the whole of the gait cycle reaching maximum at the end of stance phase probably as a compensatory action for the lack of hip extension. Sagittal hip motion is reduced especially extension from midstance through to terminal stance, this is despite the patient having more than adequate physiological hip movement to gain a greater degree of sagittal hip motion when walking. With an arc of motion limited to 35° on the affected side compared to the normal 55°, this is likely to be a pain reducing manoeuvre. Differences in hip motion in all planes on the operated and non-operated sides can be identified post surgery (Hurwitz et al, 1993). Hurwitz et al (1993) suggest that the presence of similar post operative irregular gait patterns to that found pre-operatively may be due to a learnt response from trying to reduce load on the affected side.

Investigating walking at 6 months post Charnley total hip replacement Stauffer et al (1974) agreed with the gait pattern findings of Murray et al (1971), showing that in 25 patients (mean age 63 yrs) improvement in all planes of movement took place during walking, when measured by an electrogoniometer. Sagittal plane movement increased by 20.7° to 32.8° whilst the return of movement in the frontal and horizontal planes was considerably less, 1.8° and 0.8° respectively, with three patients loosing range in the frontal plane and 8 in the horizontal. At six months, these authors reported that hip range was still considerably less than published norms at this time. In a small group of eight patients (age 64±2yrs) Ajemian et al (1997) reported results at four and eight months post THR surgery for sagittal plane motion and moments during walking. Walking speed increased from 1.00±0.04m/s at four months to 1.08±0.03m/s at eight months (Table 4.16, p105A) with flexion decreasing from 24.9±1.1° to 24.0±0.9° and extension increasing from 10.4±1.2° to 14.2± 1.4°.

Using single axis electrogoniometers at the hip and knee, Rowe et al (1989) measured flexion/ extension range in 65 patients prior to surgery and three, six and 12 months after (age 63±9 (standard error)). The average range of hip flexion/ extension increased by 54% at 12 months, from 11° to 16.94° but was still significantly less (p=0.05) than the normal range (25°) required. Flexion/ extension range in the normal hip in the THR patients remained below the normal magnitude even at 12 months, but this was not significant, as the variation in range on the non-THR side was large indicating disparity in the group. These authors also noted that patients regained 90% of their walking velocity by 12 months post-operation, with step length increasing during the first two months and cadence between two and six months.

Biomechanical asymmetry between operated and non-operated hips continues to be an issue for at least 6 months (James et al, 1994). Following 20 patients with unilateral THR, James et al (1994) demonstrated decreasing asymmetry in flexion and extension range during walking between the two sides. Passive physiological range increased by two months post op (from 65 pre to 85°) but the range did not change from two to six months. When sagittal plane movement was measured during flat walking, patients only used 24% of their available range at two months and this increased marginally at 6 months to 26%. Findings from these authors show large ranges of sagittal plane movement for both physiological and gait motion (Table 4.17, p106A).

At approximately one year post op Perron et al (2000) examined movement, force and electromyographical data from the hips of 15 non operated participants and 18 with THR, aged 65.5±6.5 and 65.6±6 respectively. Significant differences (p=0.006) were found in gait velocity 1.25±0.1 controls and 1.07±0.2 for THR (Table 4.16, p105A), as well as sagittal plane motion (both flexion and extension) during gait, with a mean 7.8° loss of hip extension at push off which the authors suggested was due to tight anterior hip structures rather than due to hip extensor muscle weakness. Movements in the frontal and horizontal planes were not statistically different between the groups but assessment of the movement / time graphs shows clear trend difference and high variability. The THR group had less frontal plane range of movement through the gait cycle especially at push off. Whilst in the horizontal plane the THR group had less movement through the cycle staying in a more neutral position than the control group. Through swing phase, the THR group rotated less

Table 4.18 Summary of measured and calculated hip forces during walking in healthy participants and those after THR

Authors (units)	**Sample size**	**Age yrs**	**Time post op**	**Max vertical**	**Max M/L**	**Max AP**
Measured						
Rydell (1966) (%BW)	THR: 2	51 56	6mth	143 264	42 96	21 92
English (1977,1979) (%BW)	THR: 1		42 days	242-256		
Winter (1984) (Nm/kg)	Non THR			0.6 **-0.4**		
Kotzar et al (1991) (*BW)	2	F: 67 M: 72	31 days 23-58	2.8±0.1 1.2-2.5±0.3		
Brand et al (1994) (*BW)	1	M: 79	90 days	2.9- 3.3		
Bergmann et al (2001) (%BW)	THR: 4	60.76±11	17±9.4	246.5± 30.4		
Calculated	**Units**	**Velocity**		**Resultant Max 1**	**Resultant Max 2**	
Stansfield et al (2002) (N/BW)	THR: 5	52.6±6.6	18.6± 4.1 mth	-4.24±0.9 **-4.43±1.2**	-0.93±0.3 **0.95±0.3**	-0.68±0.3 **0.2±0.06**
	M: 5	49.4±5		-5.19±1.2 **-6.74±1.3**	1.36±0.4 **1.46±0.3**	-1.00±0.4 **0.38±0.3**
	F: 6	49.7±5.2		-5.63±0.9 **-6.19±1.9**	1.46±0.3 **1.5±0.6**	-1.00±0.4 **0.39±0.15**
Paul (1967)	%BW			425	442	
Brand et al (1994)	*BW			3.5 - 4		
Röhrle et al (1984)	%BW	2.5km/hr		260±165	360±165	
Crowinshield et al (1978b)	%BW	1km/hr		331±118		

Key:

Winter (1984) peak measures, non bold data 0 -50 % of stance phase, **data in bold 50-100% of stance phase.**

Kotzar et al (1991) average force range Pt1=2.6-3.1, Pt2= 0.8-3.3

Brand et al (1994) measured and predicted resultant hip contact forces

Bergmann et al (2001) peak hip contact force

Stansfield et al (2002): non bold data 0 -50 % of gait cycle, **data in bold 50-100% of gait cycle** tending to hold the hip in medial rotation until the end of swing when the hip moved into lateral rotation. The slowest walking velocities were recorded by Berman et al (1991) using a gait evaluation mat rather than a walkway with force plates and no reliability data is given for the mat.

The kinematic results from different authors are varied depending on the time since surgery, the type of surgery and the instrumentation used to measure hip function during walking. Overall with time hip movement increases in magnitude and in timing of key movement and moment events.

4.5.3.2 Kinetics

As discussed in section 4.4.2.2 (hip kinetics in gait) it is difficult to compare the results of joint kinetics studies, a summary of literature can be found in Table 4.18. In patients following THR the difficulty of the analysis method has been partly removed as instrumented measurement can be undertaken. With instrumented prosthesis, hip contact pressures can be measured in vivo as well as ground reaction force and joint torques. Patterns of normal hip forces through the gait cycle can be seen for adults, children and for those with pathology (Schache & Baker, 2007; Rose & Gamble, 2006; Stansfield et al, 2002; Bergman et al, 2001; Winter, 1987).

Hip contact forces were first ascertained in those with THR by Rydell in 1966 and English (1977.1979), whilst Taylor et al (1997 and 1998) reported hip contact forces for those following massive tumour implants. From published research the general consensus reports that hip contact forces fall between 2–5 times Body Weight (BW) during normal walking (Andriacchi & Hurwitz, 1997). At less than six months following THR for OA the forces are reduced to within a range of 2.5 – 3.5BW (Andriacchi & Hurwitz, 1997, Brand et al, 1994) but these rise after six months up to a maximum of 4.3BW at 2.5 years. Brand & Crowinshield (1980) reported a similar trend in hip contact forces, in eight patients (64±2 yrs), which increased from preoperative (3.4 times BW*m) to 3.7 times BW*m at 8 months post hip replacement. Change in hip force with time may be partly explained by the natural healing process after total hip replacement but Bergmann et al (1993) suggest that although the shape of the force pattern over the gait cycle does not change with time, initially the magnitude of the curve increase but this then decreases because of training effects. This effect is not reported by other authors.

Conversely in the early post operative stages (23-58 days post surgery) Kotzar et al (1995) reported lower hip forces (2.0–2.8 %BW). These authors suggest that the highest forces did not occur during walking or assisted walking but on the unpredicted or spontaneous actions e.g. reaching, maintaining balance on a single leg, or preparing to move.

Bergmann et al (2001) calculated hip contact forces over nine activities: slow, normal and fast walking, standing up, sitting down, standing on two legs, one leg then two legs and knee bends from two legged stance, in four patients who had undergone THR (mean 17 months post THR). In the most extensive study of hip contact forces to date, they extrapolated their results to those for the "typical" patient for each of the nine activities and showed that peak hip contact forces (F_p) between 143-260 (%Body weight (BW)), cycle times between 0.96 – 6.72 s, body weight was 836 – 920N. Peak contact force was greatest going down stairs and least during knee bends. Contact forces for walking varied depending on velocity with normal walking having the least force (211-285, mean 238 %BW), slow walking (239-255, mean 242 %BW) and fast walking (218-279, mean 250 %BW). Two of the four THR participants showed a single peak force pattern during walking and the authors warn that individual variation can be considerable. Despite this variation, peak contact forces may be used to show prosthetic problems or muscle dysfunction.

Abnormal gait patterns after THR can produce greater peak contact force of up to 409%BW during walking (Bergmann et al, 2001). These authors propose that muscle dysfunction may produce an increase in contact forces as other anatomically insufficient muscles take over the role of the dysfunctional groups. This work supports that of Krebs et al (1998,1991) in their single case studies showing that the timing of peak contact pressures are most frequent between mid stance and terminal stance. Krebs et al, (1998, 1991)amongst others showed that the peak ground

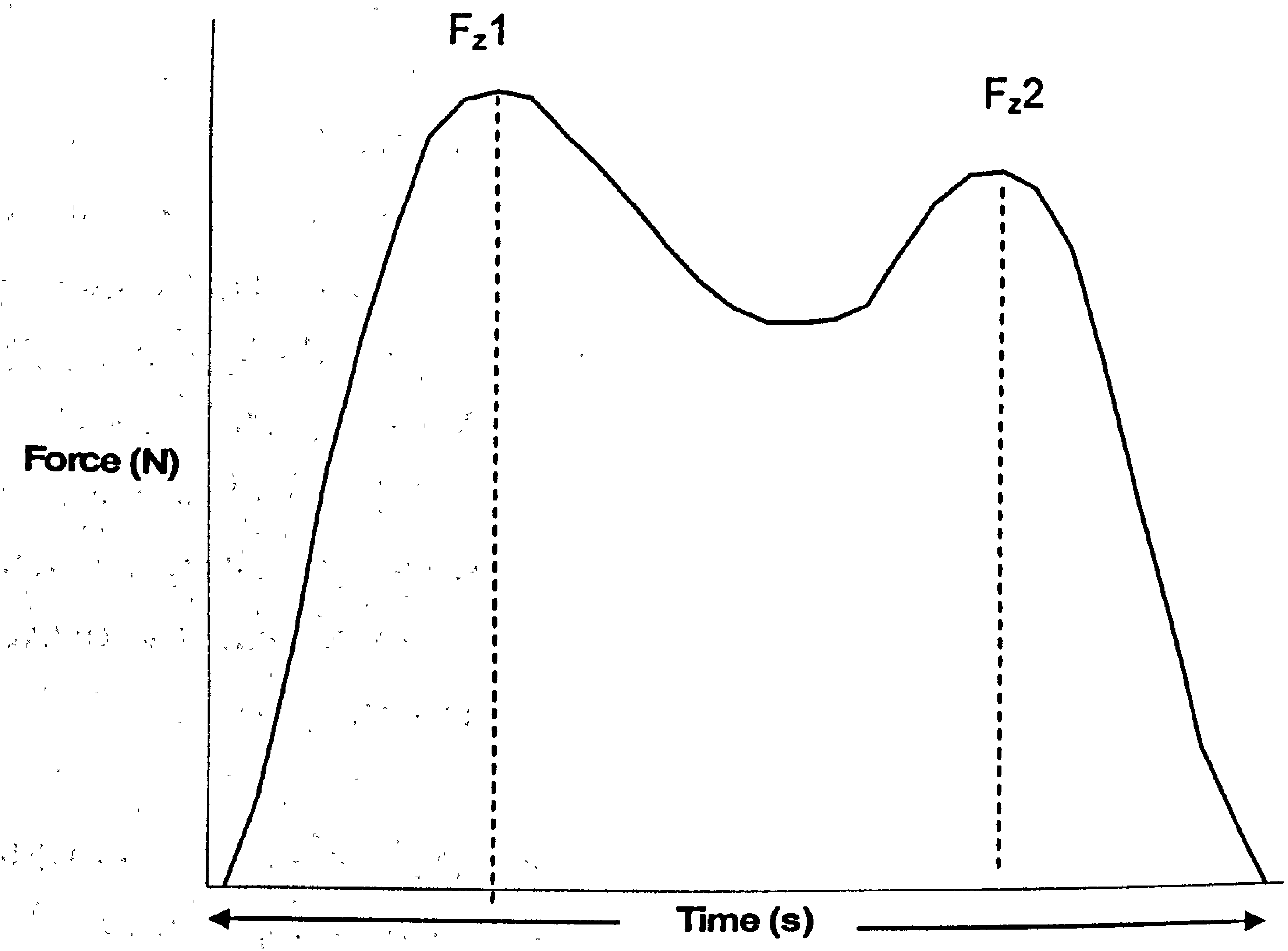


Figure 4.8 Representation of vertical ground reaction forces, F_z1 = maximal vertical force at Heel Strike, F_z2 = maximal vertical force at Toe off

reaction force and peak external flexion and adduction joint torques occur between mid stance and terminal stance (30% - 60% gait cycle).

Ground reaction force started approximately 50-100ms after the contact pressure on the instrumented acetabulum and prosthesis suggesting that the contact pressures were due to muscle contraction in preparation for initial contact. Timing of peak contact pressures differs between cases but the mass of the patient does not significantly affect the magnitude of the force, authors suggest that this is because muscle co-contraction plays an important role in reducing contact forces.

Stauffer et al (1974) reported reaction forces as a percentage of body weight for all three dimensions of motion showing that these significantly increase from pre to post operative walking indicating that patients were more able to load their operated side. The forces generated in all three dimensions followed a similar pattern to those of normal hip data. Peak forces in the vertical and fore/aft directions occurred significantly earlier in the gait cycle after surgery, but medial/ lateral forces were variable and showed no significant differences with time. The magnitude and timing of the forces found by Stauffer et al (1974) were slightly different to those reported by other authors possibly due to the type of surgery.

Although vertical ground reaction forces recover with time, there remains an asymmetry between the operated and non-operated sides for many months post op. James et al (1994) reported asymmetries at two and six months but these had recovered by five years post op. The greatest asymmetry occur in the rates of loading of each leg represented by the magnitude of the vertical force (N) at F_z1 divided by the time to this point and the magnitude of F_z2 divided by the time from this point to the end of loading (Figure 4.8). Both pre-operative measures and those at two months showed large differences to the calculations in the non operated group and when compared to those at five years. By five years post op rates of loading had returned to non operative levels.

Hip joint torques have been explored post THR during walking by a number of authors with the findings following into similar trends. In an extensive study Perron et al (2000) examined 18 female patients post THR and compared peak internal moments (Nm/kg) with a control group after controlling for walking speed. Significant differences were found in the sagittal plane at initial contact/ loading response where the THR group had a smaller extension moment ($p<0.02$) and at the transition from loading response to mid stance in the frontal plane was a lower peak abductor moment ($p=0.02$). Significant difference were also found in the transverse plane where the THR group had decreased external rotator moment ($p=0.002$) through mid stance.

The influence of muscle function on kinetics during walking was investigated by Foucher et al (2006) who for 28 patients, one year after THR demonstrated that Tensor Fascia Latae (TFL) had the strongest relationship ($p=0.001$, $R^2=0.84\pm0.014$) to the 1st peak contact force followed by the hip abductors ($R^2=0.54\pm0.22$), and then the extensors ($R^2=0.20\pm0.17$). However the abductors had the strongest relationship ($p=0.01$, $R^2=0.57\pm0.31$) with the 2nd peak contact force, followed by the flexors ($R^2=0.40\pm0.20$) and the lateral rotators ($R^2=0.21\pm0.26$). This knowledge may help design and modify rehabilitation programs in the future.

Generally hip joint torques decrease with time post THR, Ajemian et al (1997) showed that the largest internal hip moments, extension and abduction, fell from four to eight months but flexion moments increased. Hip abduction moment both pre-operatively and at four months post was much larger than that at eight months and this may reflect the increased demand on the hip abductors because of pain.

Table 5.1 Camera specification for the Kinemetrix System

CCIR standard, 625 lines,
50/100 frames/sec.
CCTV
2/3" frame transfer
CCD having 576 vertical x 576 horizontal effective picture elements.
1.0Vp-p, 75 ohm video output.
Standard C mount 16mm, f1.4 lens with infrared band pass filter.
Each camera was wall mounted.
IR Array 96x5mm in diameter GaAs infra-red LED's pulsed at 50 or 100 Hz.
One co-axial array per camera sharing a single power supply and pulse generator.
Black and white monitor with 1.0Vp-p, 75ohm BNC input.
(MIE Ltd web site)

Key:

CCIR – Consultative Committee for International Radio (standard for Digital video)
CCTV – Closed Circuit Television
CCD – Charge Couple Device
IR – Infra red
GaAS - Gallium arsenide
LED – Light emitting diodes
BNC - Bayonet Neill-Concelman connectors

5.0 METHODS - Pre trial

This chapter reports the development of the method used in the study and the reliability and accuracy of the measurement system, after introducing the instrumentation used. The following studies were undertaken:

Development of Lumbar spine marker fixation
Development of analysis program for the hip and the Lumbar spine
Accuracy and reliability of the Kinemetrix Motion Analysis System
Reliability of palpation of bony landmarks
Reliability of Marker placement
Reliability of measurement of Passive Physiological Movement
Force platform verification

5.1 OVERVIEW OF THE MEASUREMENT SET UP

5.1.1 Instrumentation for dynamic measurements

All dynamic measurements utilised the 3-D motion analysis system (Kinemetrix system, MIE Ltd., Leeds, UK). This system used infrared video technology to track automatically and analyse the movement of passive reflective markers placed in the view of the cameras. The placement of six cameras was such that each reflective marker could be recorded by at least two cameras at any time. The Kinemetrix system collected, displayed, processed and analysed the motion. Once the test had been performed the data was manipulated and viewed in a variety of different ways. The position, velocity and acceleration of each individual marker may be investigated at any time throughout the test. By defining the relationship between the markers, the data from a subject can be animated using a stick figure onto the computer screen (MIE Ltd, Kinemetrix Handbook). Data can be collected at either 50 or 100Hz.

The camera specifications are given in Table 5.1.

5.1.2 Instrumentation for Passive Physiological Measurements

The hand-held MIE Clinical Goniometer (MIE Ltd, Leeds, UK) was used to measure lumbar spine flexion and extension. It has a 360° scale, which is divided into 1° increments, weighing approximately 11 grams, it has a base of 0.7cm and measures 10cm in height. The clinical goniometer works vertically, using gravity as its reference. There is no needle, but a semi-circular column of coloured fluid and the dial is read from the bottom or lower side of the meniscus of the fluid column. The clinical goniometer is held so that the dial is vertical prior to measurement gaining a zero level and ensuring maximum accuracy. The goniometer should be held securely on the spine, ensuring that it does not move whilst testing takes place. All measurements are in degrees.

A standard 36-inch tape measure was used for the measurement of lateral flexion of the lumbar spine. A 360° Universal goniometer was used to assess the hip range of movements. This is a standard tool for joint measurement (Norkin & White, 1995) and has good reliability (see section 4.2.1.1.)

5.2 DEVELOPMENT OF LUMBAR SPINE MARKER FIXATION

Several pre trial studies were undertaken to determine the measurement requirements for the sitting to standing and bending functions but only the development of lumbar spine marker fixation will be presented.

Measurement of lumbar spine motion has to be carried out by skin marker attachment to relevant points depicting motion of the lumbar spine. Direct skin marker attachment has been shown to have greater error than plate mounted markers (Vogt et al, 2003b; Benedetti et al, 1998) and Drerup & Hierholzer (1987) have shown that marker placement over the anatomical dimples representing the PSIS, is not an exact indicator of pelvic motion. To assess a lumbar spine marker system which could be used most effectively with the Kinemetrix motion analysis instrumentation, the skin attachment systems described by Crosbie et al (1997a,b), and Whittle & Levine (1999), and the plate mounted system of Vogt et al (2003b)

Table 5.2 Analysis of lumbar marker plate system - mean angles of movement during walking (n=9), all values are expressed in degrees.

	F/E (1)	F/E (2)	Rot (1)	Rot (2)	LF (1)	LF (2)
Mean (°)	8.4	8.1	8.2	8.4	13.3	13.0
SD	1.8	1.8	1.6	1.4	1.3	1.7
Range	5	6	5	5	4	5
PPMCC	0.21		0.68		-0.22	
LSD	2.69		2.77		3.15	
LOA upper limit	3.86		3.97		4.51	
LOA lower limit	1.52		1.57		1.78	
LOA range	2.33		2.40		2.73	
T-test values (p values)	0.67		0.59		0.69	

Key: F/E Flexion Extension, Rot Rotation, LF lateral Flexion, * $p<0.05$
(1) = 1st trial, (2) = 2nd trial, PPMC = Pearson Moment Correlation Coefficient,
LOA upper limit = đ + (t x SD of difference), LOA lower limit = đ – (t x SD of difference), đ = mean of differences, t = critical value t for 8 degrees of freedom.
LSD t*SD of differences

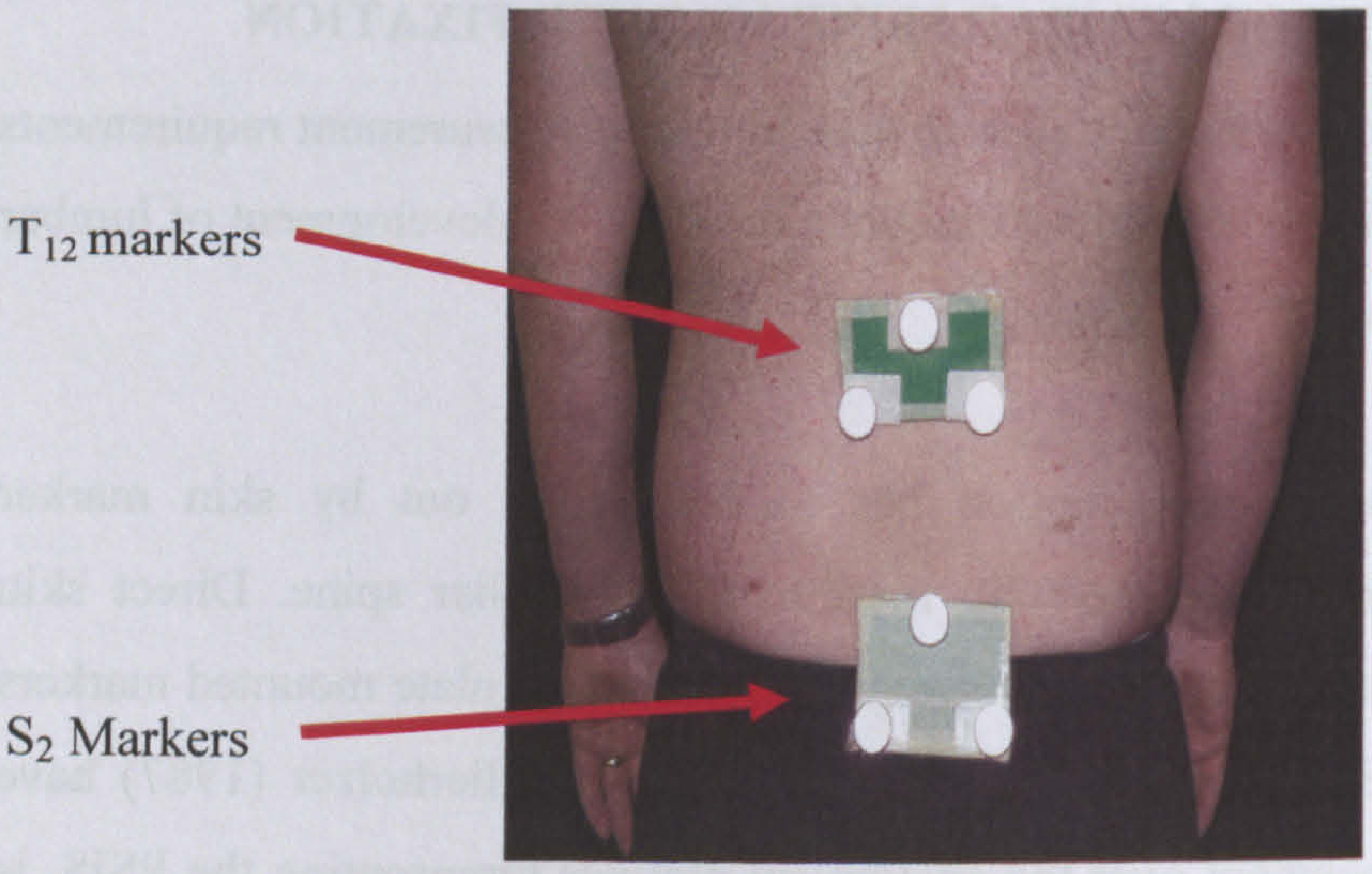


Figure 5.1 Lumbar Spine Marker Placement

were constructed by the researcher and placed on a static model. The cameras recorded one second of data with marker systems placed on the T_{12} and S_2 spinal levels. The markers used in Crosbie et al (1997a,b) and the Vogt et al (2003b) were more easily seen, given the dimensions of the laboratory, camera position and materials available along with efficient measurement of the hip and lumbar spine. As both the Crosbie and Vogt systems could be seen easily the plate mounted system was used to reduce marker placement error (Vogt et al, 2003b) and save trial time (Benedetti et al, 1998). A modified marker system was then developed using a plastic square with three markers. A small test retest study was then undertaken on 9 healthy adults to assess T_{12} and S_2 attachment reliability during walking. The results can be found in Table 5.2, indicating that there was no significant difference on repeat testing with mean differences of 1.9±1.2°, 0.2±1.2° and 1.9±1.4° and low Limits of Agreement. Pearcy et al (1987) found the maximum error of their opto-electronic system to be ±2° and the results from the present study are comparable. The plastic plates could be used successfully to represent lumbar spine motion.

Once the marker system was established, fixation was tested to ascertain the most secure attachment. The researcher made two spinal marker systems with different fixation; one fixed with double-sided sticky tape alone, and the other fixed with a belt going around the pelvis and thorax as well as double-sided tape. Each system had three reflective markers; one was attached at the centre upper portion of a rectangle of plastic and the other two to the corners of the lower end (Figure 5.1), part of a 15cm ruler was placed at the lower end of the plastic to act as counterbalance.

18 subjects (9 male and 9 female) performed five walks with each spinal measurement system placed at the T_{12} and S_2 levels. The fascia over the T_{12} spinal process is relatively fixed to the bone therefore skin movement is moderately representative of bone movement (Lundberg, 1996). Skin marker placement over S_2 is regarded as having minimal error (Vanneuville et al, 1997; Drerup & Hierholzer, 1987).

Table 5.3 Analysis of two lumbar marker attachment systems - mean angles of movement during walking (n=18), all values are expressed in degrees.

	F/E with belt	F/E without	Rot with belt	Rot without	LF with belt	LF without
Mean (°)	10	8.44	6.89	6.44	13.50	12.89
SD	3.55	1.50	2.08	2.53	1.54	1.64
Range	4 -15	6 – 11	3 -11	2 -11	11 -17	10 -15
PPMCC	-0.29		0.87*		-0.21	
LSD	5.62		1.43		2.63	
LOA upper imit	9.17		2.54		4.80	
LOA lower limit	-2.06		-0.32		-0.47	
LOA range	11.23		2.86		5.27	
T-test values (pvalues)	0.1		0.15		0.26	

Key: F/E Flexion Extension, Rot Rotation, LF lateral Flexion, * $p<0.05$

PPMC = Pearson Moment Correlation Coefficient,

LOA upper limit = đ + (t x SD of difference), LOA lower limit = đ – (t x SD of difference), đ = mean of differences, t = critical value t for 17 degrees of freedom.

LSD t*SD of differences,

The spinal measurement system was removed from the participant's back after completion of the first set of walks and then replaced again before the next set. There was random allocation of walking with the belt or no belt first. A 30-minute rest was given before undertaking the second set of walks.

Participants were asked to walk at their normal pace over a 10-metre walkway and to look straight ahead at all times and five sets of data were collected per fixation system. Data was collected during one stance phase when the participant's limb was placed on the force plate. For both sets of data (spinal measurement system with and without a belt) means and standard deviation were calculated (Table 5.3) and the Pearson Product Moment Correlation Coefficient (r), LOA (Limits of agreement) and the paired t-test were used for statistical analysis.

5.2.1. Results

Table 5.3 collates the mean and standard deviations and statistical analysis for lumbar spine movement during walking wearing both marker systems.

There was no significant difference between the range of lumbar movement when comparing the two marker systems when assessed by the paired t-test ($p>0.05$). Flexion/ extension indicated the greatest differences in values and the largest standard deviations, with the belt system producing larger values than without. Movement with the belt on was always greater than without. For both rotation and lateral flexion, the LOAs were acceptable indicating that the systems were only interchangeable for these movements. As a result of the larger variance for flexion, the LOA limits are larger for this movement indicating that the two marker systems are not interchangeable. A significant correlation ($p<0.01$) was found between the rotation angles with and without the belt, but not for the other movements, hence there was no relationship between the sets of data, except for spinal rotation.

As the two marker systems were not interchangeable a decision had to be made on the system to be used. The participants all reported that the belt system was uncomfortable especially around the chest, with a restriction on chest movement in particular. As the system without the belt attachment gave smaller variance for the most complex and largest movement (flexion), this marker system was chosen to be used in the main study.

5.3 DEVELOPMENT OF ANALYSIS PROGRAM FOR THE HIP AND LUMBAR SPINE

To assess movement around the true centre of joint rotation, marker data collected by the Kinemetrix software was entered into a program, which calculated the position of the joint centre. An original software programme was written by Dr David Hooper, Bioengineer at University of East London (1996 – 1999) using Fortran ++ to process the data and to allow presentation and analysis/ manipulation in Matlab (4.2c.1). The program was designed to study three-dimensional analysis of the knee and ankle movement during walking and stair climbing and was then adapted to accommodate measurement at the hip joint. Several researcher papers have been published using this program (Morrissey et al (2004), Hooper et al (2002 a&b, 2001), Goodwin et al (1999)) to assess knee joint range and torque. Unfortunately the programmes were flawed for hip analysis so alternative analysis procedures were investigated. Tim Pitt, (Vaquita Software) wrote an ASCII plugin programs for analysis in Vicon Workstation and BodyBuilder to allow the data to be imported from an ASCII file to Workstation for segment marker identification and setting event markers. The files were then opened in BodyBuilder, where a model was applied for lower limb analysis of joint movement, forces and moments and another for lumbar spine movement. Diagrammatic representation of marker placement and the convention for axes and motion are given at the start of Appendix C before a complete version of both the programs for hip and lumbar spine angles.

The program requires the identification of nine markers on the lower limb and pelvis with particular importance on the lateral femoral condyle, anterior shank and anterior shin markers. On the pelvis good identification of the two ASIS markers and the S_2 marker are essential.

5.3.1 Hip program

The ASCII plug in program for the hip was developed using the method of identifying hip joint centre (HJC) outlined by Bell et al (1989, 1990), first described by Cappozzo in 1984 and bearing in mind the recommendations of Wu & Kavanagh (1995). The method is based on the premise that:

1) The thigh is a rigid body and
2) The hip centre is the centre of a sphere described by the three-dimensional rotation of a point on that body. (Cappozzo, 1984)

The pelvic bony landmarks used were both Anterior Superior Iliac Spines (ASIS) and a central marker bisecting the line between the Posterior Superior Iliac Spines (S_2). The Greater Trochanter (GT) and Lateral Femoral Condyle (LFC) were also identified to give the estimation of femoral length. Using the two ASIS markers, the width of the pelvis was calculated and then using the bisection point of this line, the depth of the pelvis was estimated to the S_2 marker. The distances between the bony landmarks: GT, ASIS and the S_2 were calculated and formulated to ascertain the true central position of the hip joint.

Stagni et al (2000) reviewed the different models for calculating the HJC. This research is the latest test of mislocation of HJC. Some previous studies however looked at the comparison of the main non-invasive means of calculating the HJC. There are two main categories:

1) Prediction approach: uses anatomical measurements of the pelvis to describe a regression equation.

- Bell model: as described above,
- Tylkowski et al (1982) percentage posterior model:
- Andriacchi et al (1980) and Andriacchi & Strickland (1983) models: measuring the distance from the ASIS to the symphysis pubis with modifications in all three planes
- Davis et al (1991): Equation using the ASIS and the symphysis pubis

Table 5.4 Comparison of accuracy of HJC position (using 95% confidence intervals) Taken from Bell et al (1989).

Approach	2 dimensions (frontal plane) (cm)		3 dimensions (cm)
	Children	Adult	Adults
Tylkowski et al (1982)	1.5	2.7	3.3
Andriacchi et al (1980, 1982, 1983)	1.1	1.6 (women) 1.8 (men)	
Combined			2.6

- Seidel et al (1995) an alternative equation to Davis et al, using the ASIS and the symphysis pubis but more difficult to palpate so used on cadavers. Established on 65 adult cadaveric pelves.

2) Functional model:

- Cappozzo (1984) estimates the HJC as the pivot point of a 3-D relative movement between the femur and the pelvis. The two adaptations of this model using the x percentage as -4% and -22% were also validated by Shea et al (1997).

Bell et al (1989) tested the accuracy of the HJC calculation method they proposed with those suggested by Tylkowski et al (1982), Andriacchi et al (1980) and Andriacchi & Strickland (1983), using pelvic x-rays from 31 adult and 39 children. The HJC was identified as the centre of a series of concentric circles, which matched the size of the head of the femur. A further 20 skeletal pelves were marked on both the ASIS and pubic tubercles, and AP and lateral x-rays taken within a wire cage. These were used to calculate the distance from the ASIS to the HJC in the AP direction.

Bell et al (1989) found that the real HJC location averaged 30% distal, 14% medial and 22% posterior to the ASIS as a percentage of the ASIS-ASIS separation. Using a combination of the frontal plane approach of Andriacchi and the posterior percentage of ASIS-ASIS distance (Tylkowski et al, 1982) predicted the most accurate location of the HJC to within 2.6cm of the true location in adults (Table 5.4).

In a further study using this new combined approach of locating the HJC and using the same marker system, Bell et al (1990) studied seven healthy men aged 38 – 53 years (mean 46.6yrs.) using the marker system identified above. Data from two repeated three second tests of hip flexion, extension and abduction were gathered using Vicon Motion analysis. Each subject also had a pair of oblique x-rays taken with a large wire radiographic surveying device to give a fixed reference frame.

Estimation of the HJC could be undertaken from this as well as confirmation of the position of the surface markers. The rotational method (Bell et al) predicted that the HJC was located an average 3.79±1.9cm from the true x-ray HJC location. The Andriacchi and Tylkowski approaches predicted the HJC to be within 3.61cm and 1.9cm, respectively. The Andriacchi approach again predicted well in the AP direction but the overall estimate was very similar to the rotation method.

Using the Andriacchi method, Bell et al (1990) indicated that the greater trochanter marker position gave an accurate estimate of the AP HJC location, but that the point 1.5-2cm distally from the midpoint of the ASIS to pubic symphysis line was not a good estimate of frontal plane position. The best estimate of HJC location was the combination of the Tylkowski approach with the Bell reference frame percentages of 30% distal, 14% medial and 19% posterior to the ASIS as a percentage of the ASIS-ASIS separation from the skeletal pelves.

The difference in the reference frame percentages between the 1989 and 1990 Bell studies was probably due to the difficulty in estimating the exact AP locations of the ASIS bony landmarks from the skin markers. This would pose difficulties particularly in obese participants.

McGibbon et al (1997) examined the in-vivo and ex-vivo estimation of HJC along with the equations from 4 others (Andriacchi, Tylkowski, Bell, Seidel) and found that their prediction equation was the most accurate closely followed by the calculations of Bell et al (1989) who were within 1.5 cm from the in-vivo calculations.

In 1999, however, Kirkwood et al (1999a), reported results of miscalculation of the HJC using 4 methods: a) Seidel et al (1995), b) Bell et al (1989, 1990), Andriacchi's ASIS / symphysis pubis model with two modification c) with medial and lateral correction (Andriacchi et al, 1980) and d) modified in the medial/lateral, distal/proximal and vertical directions Andriacchi and Strickland (1983). The results indicated that model d) gave the most accurate position of the HJC compared to an x-

Table 5.5 Comparison of mislocation errors affecting the Hip joint centre pelvic co-ordinates - Mean & Standard Deviations (SD) (Stagni et al, 2000)

Approach	Abduction/ Adduction (X)(mm)	Medial/ Lateral rotation (Y) (mm)
Functional (Cappozzo, 1984)	3.8 (6.1)	2.5 (5.9)
Bell et al (1989, 1990)	-7.2 (5.5)	-18 (10)
Davis et al (1991)	-11.6 (16.7)	
Andriacchi et al (1980, 1983)	-7.3 (4.8)	
Tylkowski et al (1982)	-16.6 (11.6)	

ray method, with the HJC lying 1.5-2cm directly below the mid point between the ASIS and the symphysis pubis. Palpation of the symphysis pubis is always a difficult undertaking and this seems to be the greatest problems with this method.
Also in 1999, Leardini et al validated the functional method (Cappozzo, 1984) against the prediction methods of Bell and of Davis. Their research established that the functional method performed significantly better in estimating the HJC position than either of the other models but they identified that good hip range of motion was required to gain the best results using this model.

Stagni et al (2000) reviewed the different methods of calculating the HJC (Table 5.5) showing that the functional method (Cappozzo, 1984) gave the lowest mislocation error and the Bell method (Bell, 1989) the next best. These authors, in agreement with Leardini et al (1999), recommended that the functional model be used when appropriate but cannot always to be applied because of a lack of hip joint range in some patients.

Exploring the effects of hip joint centre (HJC) mislocation on gait analysis results on five young participants (25-29 years, velocity 0.84-1.19m/s), Stagni et al (2000) reported that hip joint moments are the most affected by any mislocation. The flexion/extension moment is mainly affected by anterior/posterior mislocation with a propagated error of -22% with an anterior mislocation of 30mm. Abduction/Adduction moment is affected by a medial/lateral error with a propagated error of -15% with a lateral mislocation of 30mm. The smallest moment error was for axial rotation with an error of 0.1-0.5%. This research also noted that a 30mm posterior mislocation of the HJC produced a delay of the flexion/extension timing of 25% of the stride, rendering comparison with other research studies very difficult.

Hip angle data (flexion/extension) was negligibly affected by mislocation with a mean error lower than 1° in a range of 35° and both abduction/adduction and axial rotation angles had an error of lower than 0.5° in a range of 10°. Interestingly, the effect of HJC mislocation on knee angle and moment data was negligible as errors of

1.5°, 0.04° and 0.15% (BW*H) with ranges of 5.3 and 3.2% (BW*H) for flexion/extension and Abduction/adduction components.

Piazza et al (2001) estimated the effect of limited hip joint motion on HJC location accuracy using the functional model (Cappozzo, 1984) and found that there was no evidence to support the assumption highlighted by Stagni et al (2000). However the Piazza study was undertaken using a mechanical model and not on healthy adult population and therefore should be viewed with caution.

Given the mislocation results above (Stagni et al, 2000) and as the current study involves patients after THR with the added difficulty of potential restriction in hip range (Stagni et al, 2000) who were all of an elderly population, the Bell model was used for the hip program for this study. Identification of the bony landmarks outlined above with the Bell reference frame percentages of 30% distal, 14% medial and 22% posterior to the ASIS as a percentage of the ASIS-ASIS separation (Bell et al, 1989)

5.3.2 Lumbar Spine Program

Using the methods outlined by Crosbie et al (1997a,b) and Whittle et al (1998) and Whittle & Levine (1999) an ASCII plugin program was developed for Workstation and then Bodybuilder to ascertain the three-dimensional movement of the lumbar spine. Three markers were placed at the upper and lower ends of the lumbar spine (T_{12} and S_2) to describe the segments denoting the ends of the lumbar spine. A set marker file identified each of the 3 markers in each of the segments. For each participant, a subject parameter template file was generated to identify a static position or calibration point allowing the model to calculate the orientation of the pelvic segment relative to the thoracic segment. This file also sets the estimation of the depth of the markers. Using the segment marker file and the parameter template file the Body Builder model calculated the relative angles between the identified segments to give an angle for each plane of lumbar spine motion (X, Y, Z).

5.4 RELIABILITY TESTING

Reliability of any measurement is dependent on three possible types of errors: the researcher, the tool itself and the environment being used. To assess the reliability of the researcher both palpation of bony landmarks and marker placement were evaluated and as researcher error may also occur when processing the data this was also observed. Reliability of the Kinemetrix motion analysis system is discussed in section 5.4.2 and the tools used to assess the physiological passive movement in section 5.4.4. Discussion on the force platform will be undertaken in section 5.5.

To standardise the environment in which data was collected measurements were taken at either 11 a.m. or 2.30 p.m.

5.4.1 Reliability of palpation of spinal bony landmarks

Palpation of the bony landmarks around the lumbar spine and pelvis are clinically notoriously difficult to find and may give rise to inaccurate placement, although Lundberg (1996) states that there is less error over spinal palpation to that at the hip. Salisbury and Porter (1987) showed that on only 3% of occasions did experienced non-medical staff fail to locate accurately the correct spinous process identified by either ultrasonography and by palpation. Therefore inter-rater and intra-rater reliability of lumbar spine palpation was assessed.

The spinous processes of the lumbar vertebrae were palpated in 10 healthy females in standing with the spinal muscles relaxed using method described by Burton (1986) and Hindle et al (1990). Skin secretions were removed from the subjects with alcohol wipes. To locate specific lumbar vertebrae, a level was placed on the iliac crests and a line was drawn across horizontally. If the line fell on a spinous process it was considered to be the level of the vertebrae L_4 (Burton, 1986). The first tester palpated and marked, with a dash (-) using the 'Topline UV Property marker', the centre of the lumbar spinous processes for L_1 – L_5. This produces an invisible line, which can only be viewed with a 'Topline UV lamp'. The ink was allowed to dry and the model was permitted to get up from the plinth and move about.

Approximately 30 minutes later the first tester re-marked the spinous processes with an alternative mark (l) using exactly the same method. After both tests the marks were viewed using a 'Topline UV lamp', the vertical distance between the centre of the two marks was measured and recorded. After a further 30 minutes the model returned and the second tester marked the skin using a different mark (x) repeating the method outlined above. Once again the vertical difference between the mid points of first tester first mark (-) and the second tester's mark (x) was measured and recorded.

The mean error deviation for the palpation tests of L_1 to L_5 was 5 mm. The greatest intra-palpator error occurred at L3 (5.2±5.58 mm) and the greatest inter-palpator error was at L_1 (4.4 ±4.28 mm). Following review of the literature, this error was regarded as acceptable for palpation of the lumbar spine. Lower limb bony landmark identification was undertaken by assessing the reliability of marker placement (see section 5.4.3).

5.4.2 Accuracy and reliability of the Kinemetrix Motion Analysis System

5.4.2.1 Accuracy of the Kinemetrix Motion Analysis System

The full findings of the accuracy of the Kinemetrix Motion Analysis System can be found in: Thornton, M, Morrissey M, Coutts F. (1998) Effect of camera placement on the accuracy of the Kinemetrix three-dimensional motion analysis system. *Clinical Biomechanics* 13 (6): 452-454.

With two cameras fixed at the smallest separation setting (15° horizontal, 0° vertical), the Kinemetrix was unable to calculate the three-dimensional co-ordinate of the marker. For all other camera positions tested (horizontal camera separations: 15, 30, 45°, vertical separations of 0, 15, and 30°), the errors in measurements were small (mean absolute errors less than 2 mm). The distance between the cameras and the object was always maintained at 4 m. During each test the marker was moved a known horizontal distance along a line bisecting the horizontal angular separation of the two cameras.

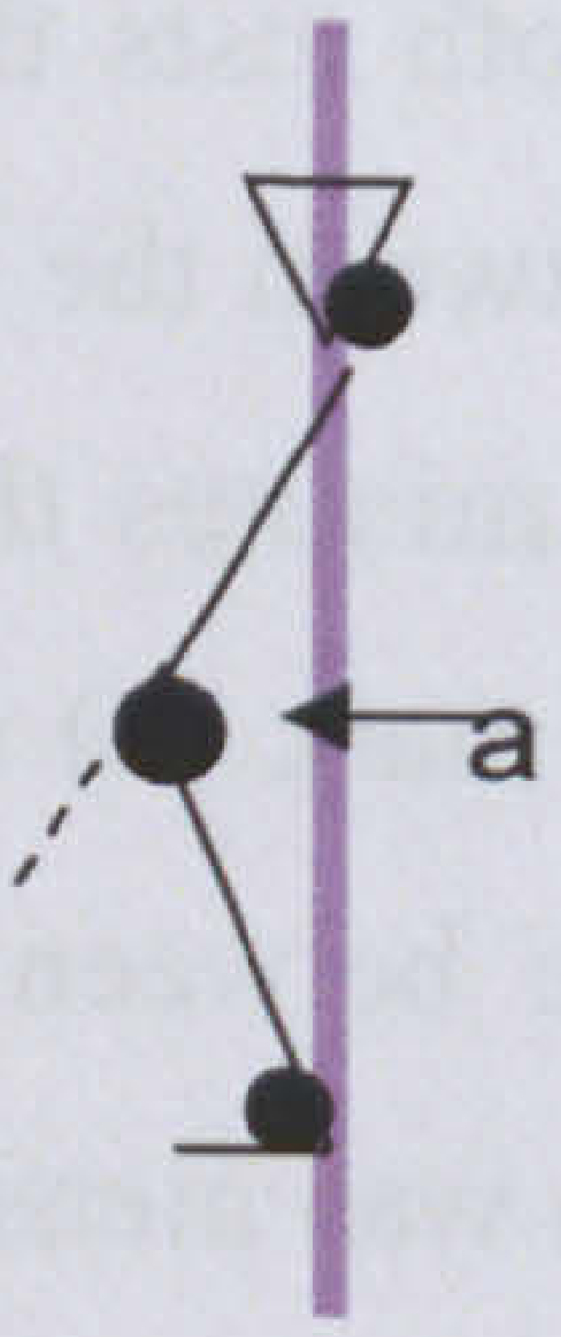


Figure 5.2
Schematic diagram of the knee joint model and measurement by the Kinemetrix motion analysis system.
Angle a) measured by the goniometer (80°)
• Reflective marker position

Table 5.6 Comparison of knee model angle to Kinemetrix motion analysis system

Position in horizontal plane	Mean 3D knee flexion angle (°)	SD	Mean difference from known angle 80°
30° right	81.58	0.13	1.58
15° right	81.59	0.06	1.59
Neutral	81.30	0.04	1.3
15° left	80.64	0.06	0.64
30° left	81.36	0.12	1.36
Mean	81.29	0.08	1.29 ± 0.39

The accuracy of the Kinemetrix Motion Analysis System was assessed as acceptable as the mean absolute error was less than 2mm and complies with the manufacturer's specifications.

5.4.2.2 Kinemetrix ability to measure a static known angle

To test further the accuracy of the Kinemetrix system an angle created by a two dimensional rigid static angled frame, was created, which was rotated through the horizontal plane in 15° intervals. Two lengths of wood (45cm * 2cm * 1cm) were held together by a screw and bolt to form the axis of the pseudo hinge joint. The free ends were attached to a vertical pole with tape so that the angle of the pseudo hinge joint represented 80° (measured by a standard 360° universal goniometer). Reflective markers (25 mm) were placed at the distal ends of each piece of wood, and one to the centre of the hinge joint (Figure 5.2). The pole of the model was then set on a stand and 3-D data was collected with the Kinemetrix motion analysis system.

The joint was placed in neutral alignment and then positioned at an angle of 15° and 30° in the horizontal plane to each side. The order of testing was right 30°, then right 15°, neutral, left 15° and finally left 30°. The rotation angles were identified by wooden stops set at 15° & 30° to the left and right of the neutral position. Data was collected for one second at 50Hz for all 5 positions and the mean data with SD are presented in Table 5.6.

There was a mean error of 1.29° when measuring a known angle of 80°, over a 60° range in the horizontal plane. The functions chosen for this study have a rotation range in the horizontal plane considerably smaller than the 60° recorded in this pilot study, and therefore this error and precision are acceptable. There does not appear to be a trend in the error, with the values changing inconsistently over the range, with the greatest change from 15° to 30° left and neutral to 15° left.

5.4.3 Reliability of marker placement

To test the reliability of marker placement, a repeated measures study was undertaken on both a static and a live model.

5.4.3.1 Reliability of marker placement on a static model

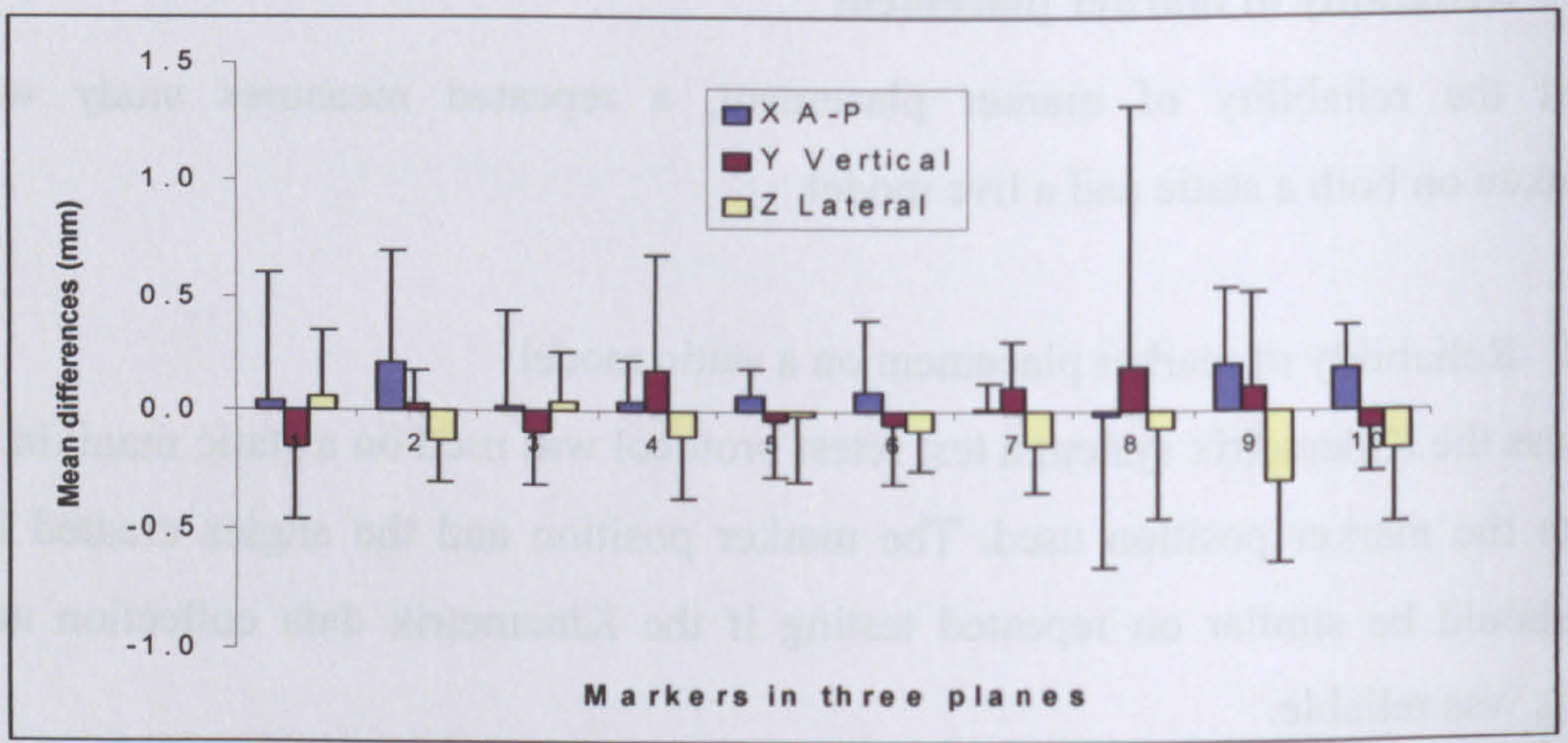
To assess the Kinemetrix system a test retest protocol was used on a static manikin to emulate the marker position used. The marker position and the angles created by them should be similar on repeated testing if the Kinemetrix data collection and analysis was reliable.

The researcher placed indelible pen marks on the manikin over the approximate position relating to the anatomical landmarks emulating the dynamic test protocol, these were:

- inferior tip of both ASIS, (ASIS)
- spinous process of 2nd sacral vertebrae, (S_2)
- inferior tip of the Greater Trochanter (GTR),
- Anterior aspect of the thigh at 56% distance from GT to LFC, (Ant thigh)
- lateral femoral condyle (LFC),
- anterior aspect of the shank at 56% distance from LFC to LM, (Ant shank)
- lower tip of the Lateral malleolus (LM),
- lateral aspect 5th metatarsal (MT).

A clinically experienced therapist identified relative anatomical points on the manikin. These are obviously not real anatomical points but estimations, however as the marks were being re-used and no repeated palpation was needed reliability of the software program could be tested. The use of the manikin is limited but it provides a true static model in a moderately human form.

Retro-reflective markers (25mm) were placed over these landmarks, and a one-second static test was recorded at 50 Hz using the Kinemetrix Motion analysis system. Once the data had been verified on the computer, the markers were removed and the procedure repeated 20 minutes later, replacing the markers on the indelible



Key:	Marker position	Key:	Marker position
1	Lateral Malleolus	6	L ASIS
2	Spinous process S_2	7	R ASIS
3	5th Metatarsal	8	Lateral femoral condyle
4	Anterior Thigh	9	Greater Trochanter
5	Anterior Shank	10	Shoulder

Figure 5.3 Mean marker positional differences (mm) in all three planes

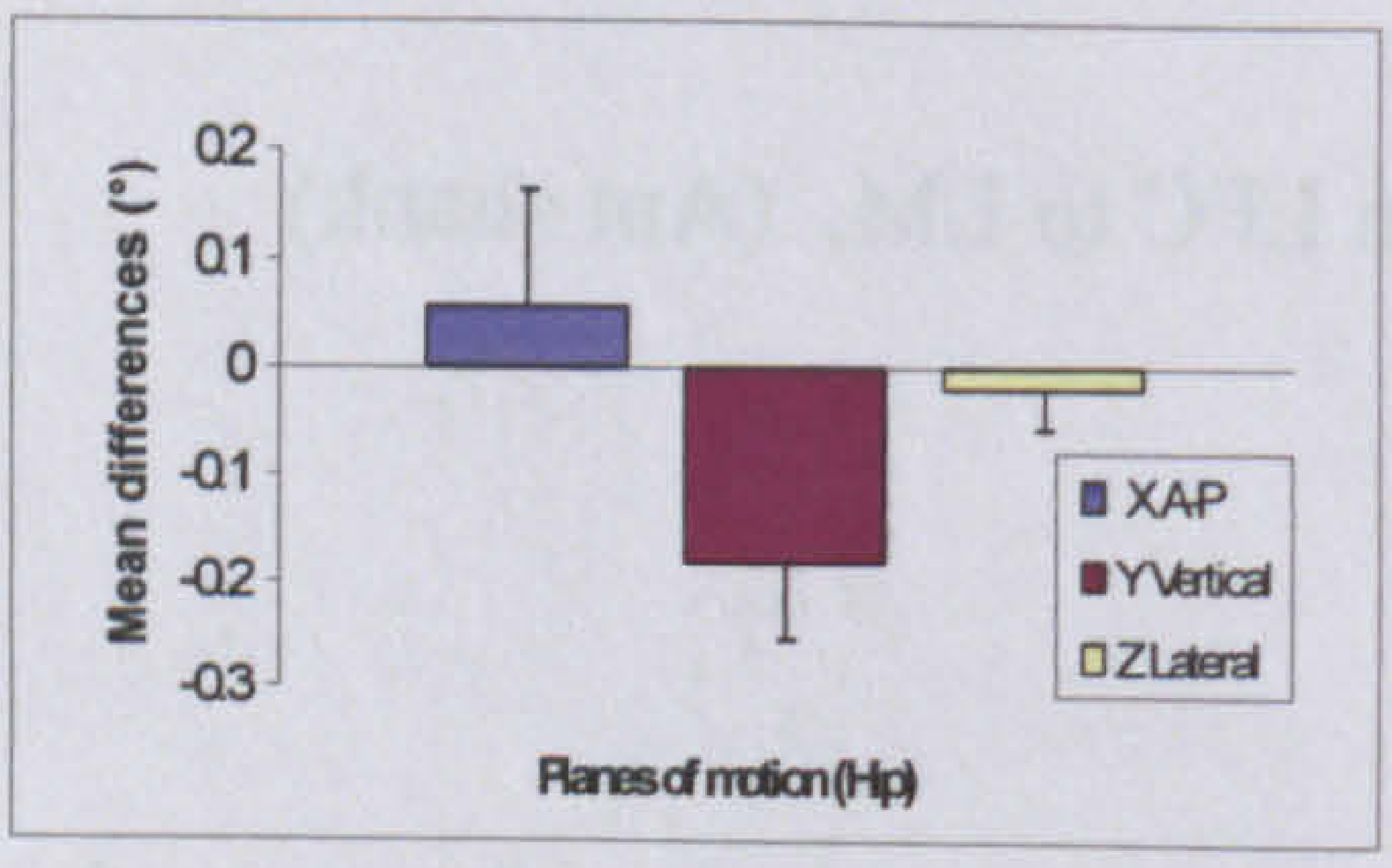


Figure 5.4a Mean differences in Hip angle (°) in three planes

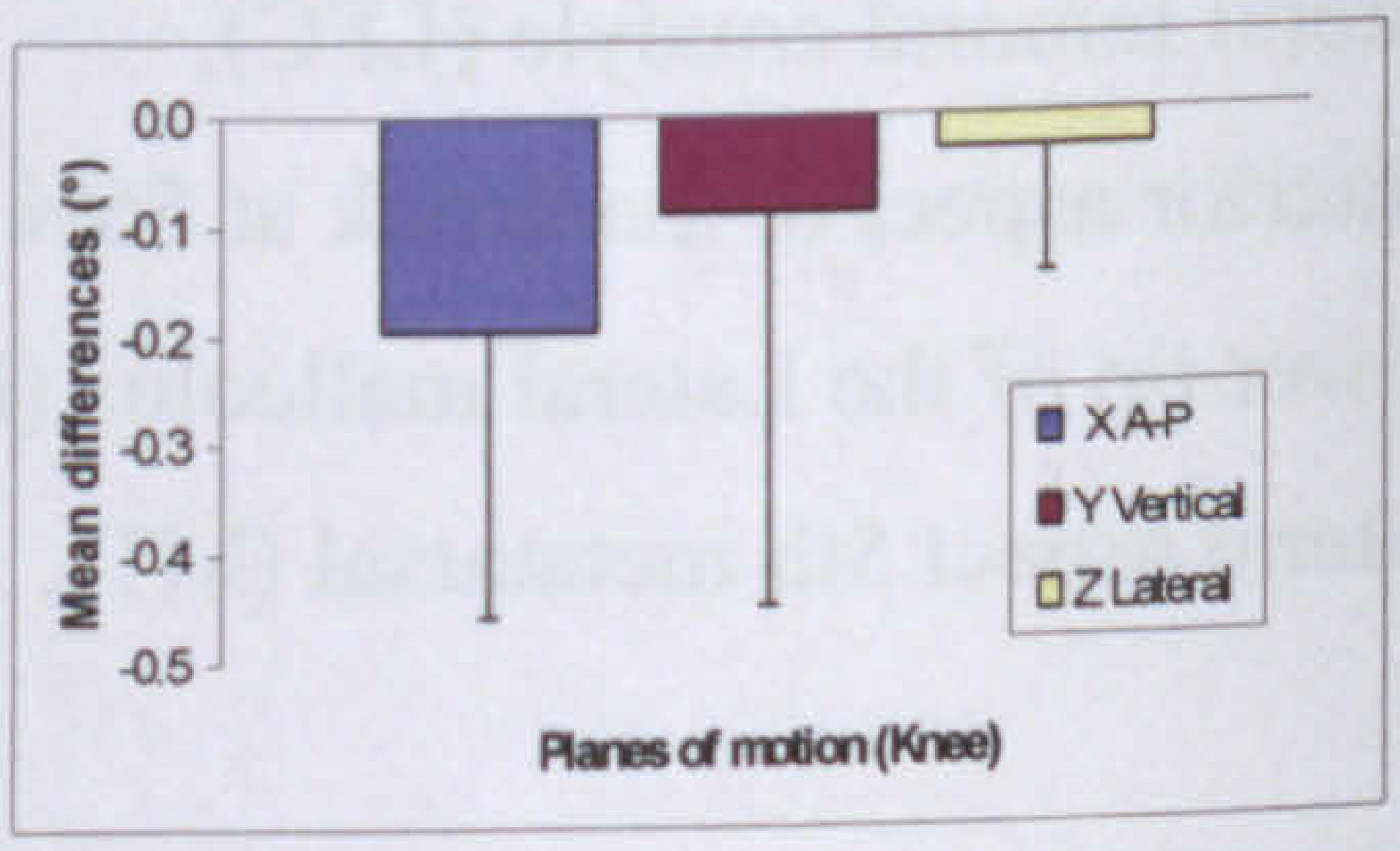


Figure 5.4b Mean differences in Knee angle (°) in three planes

marks. The test was repeated on eight occasions. The position of each marker was calculated by the Kinemetrix system, and the position data downloaded in ASCII format into Excel 97. The mean and standard deviations of the differences were calculated for all the data and then plotted (Figure 5.3).

Although the mean difference for all the markers was small (<0.5mm) the standard deviations vary greatly particularly in the vertical direction (Y) and especially at the knee joint (±1.12 mm).

To assess the effects of the positional differences the marker data was processed through the Kinemetrix software and the reliability of the angle created by the markers for the hip and knee joints were assessed (Figure 5.4 (a & b), p125A). The mean differences in hip and knee angle in each direction are small (<0.2°) with the hip angle differences being smaller than the knee. The standard deviations are larger at the knee than the hip especially in the vertical direction. Overall the differences in the positional data and the hip and knee angles are small and within acceptable ranges, therefore the Kinemetrix system and software was regarded as reliable.

5.4.3.2 Reliability of marker placement on a live model

The researcher placed markers emulating the test protocol as described in section 5.4.3.1. In addition the spinous process of T_{12} was also identified and the three-marker plates for measurement of the lumbar spine were placed at S_2 and T_{12}.

The test procedure replicated that for the manikin test except that after the three sets of data were collected on day one, the markers were removed, the surface or skin was cleaned and the procedure was repeated the next day at the same time. The mean data for each day was collated. Six individuals were measured in the erect standing position. On each occasion a 1-second period of data collection was undertaken at a sampling frequency of 50Hz.

The three dimensional hip and knee angles and the lumbar spine position in the sagittal, frontal and horizontal planes were calculated using the Kinemetrix motion analysis system for each of the tests. The difference in the mean data for test 1 and

Table 5.7 Reliability of marker placement on a live model. Descriptive analysis of the differences, t-test and LSD results for test retest hip and knee angle.

	Absolute Differences between test 1 and 2	
Subject	Hip (°)	Knee (°)
1	2.85	8.4
2	5.4	7.32
3	1.2	5.45
4	5.6	3.44
5	5.65	0.37
6	6.5	4.16
Mean of differences	4.53	4.86
SD of differences	2.0	2.9
t-test (p value)	-0.39 (0.71)	1.7 (0.15)
LSD (°)	5.26	7.41

Table 5.8 Reliability of marker placement on a live model. Descriptive analysis of differences, t-test and LSD results for the test retest Lumbar spine data

	Absolute Differences between test 1 and 2		
Subject	Sagittal (°)	Horizontal (°)	Frontal (°)
1	1	1	1
2	1	2	1
3	2	0	1
4	2	0	3
5	0	2	4
6	5	2	3
Mean of differences	1.83	1.17	2.17
SD of differences	1.72	0.98	1.33
t-test (p value)	1.77 (0.14)	0.81 (0.46)	0.8 (0.46)
LSD (°)	4.43	2.53	3.42

test 2 was compared and a paired t-test and LSD were undertaken. The hip and knee data are presented in Table 5.7 and that for the lumbar spine in Table 5.8.

Neither of the t-test results were significant indicating no significant difference between the 1st and 2nd set of data. The standard deviation of the differences for hip and the knee were comparatively small, thus the LSD are small, indicating that a change of 5.26° at the hip and 7.41° at the knee would have to occur before real change had taken place. The result for knee marker placement indicates that extra care should be taken on palpation and placement of the bony markers especially at the lateral femoral condyle.

The differences between the 1st and 2nd tests for lumbar position in the sagittal, horizontal and frontal planes are presented in Table 5.8. The differences are small with a mean of less than 2.5° between the 2 tests. The standard deviations are also small indicting a small degree of variability. None of the t-test results are significant and the LSD values are all less than 5°, indicating good reliability.

Placement of the spinal and hip markers gives good reliability but care should be taken when placing the knee joint markers.

5.4.4 Reliability of the measurement of Passive Physiological Movement

The intra-observer reliability of the measurement of passive physiological motion was tested for all lumbar spine and hip movements. The hip and lumbar spine range was measured on two separate occasions for 10 participants using the procedure described in the test protocol (section 6.4). The raw data for the measurement can be found in Appendix D and the results of lumbar spine data in Table 5.9 (p128A) and hip data in Table 5.10 (p128A).

5.4.4.1 Lumbar Spine

The mean difference and standard deviations of the differences between the two sets of test retest data are small for lateral flexion. Those for flexion and extension are larger but not unduly (Table 5.9).

Table 5.9 Reliability of passive physiological lumbar spine movement (n = 10)

	Lateral Flexion (R) (cm)	Lateral Flexion (L) (cm)	Flexion (°)	Extension (°)
Mean of 2 tests	23.98	23.69	50.85	29.67
SD of 2 tests	3.94	3.87	5.79	12.16
Mean difference between test 1 & 2	0.16	0.08	2.09	1.60
SD difference between test 1 & 2	0.08	0.08	1.90	1.76
LSD (units of measure)	0.42	0.24	6.33	4.91
Pearson Product Moment Correlation Co-efficient (r)	0.99**	1.00**	0.92**	0.98**
CoV	16.44	16.35	11.39	40.98

Key: ** significant at $p<0.001$

Table 5.10 Reliability of passive physiological hip movement measured by a 360° Universal Goniometer

	Flexion	Extension	Abduction	Adduction	Rotation	
					Lateral	Medial
Mean (°)	143.0	18.5	42.20	27.35	65.0	30.4
SD	4.43	1.55	2.82	3.21	3.15	3.062
Mean Diff (°)	1.6	1.0	1.4	1.1	1.4	1.2
SD Diff	1.51	0.47	0.7	0.88	0.84	1.03
LSD (°)	3.87	2.43	3.41	3.28	3.81	3.66
PPMCC (r)	0.93**	0.85**	0.87**	0.9**	0.94**	0.89**

Key: SD – Standard deviation, Mean Diff - Mean difference between test 1 & 2
SD Diff - SD difference between test 1 & 2, LSD - Least Significant Difference
PPMCC – Pearson Product Moment Correlation Co-efficient (r), $^{**}p<0.001$

The Pearson Product Moment Correlation Co-efficients for all four lumbar measures were high and reliable with values between r = 0.92 – 1.00, with significance of $p<0.001$ in all cases. The least significant differences however were varied, with flexion having the highest value of 4.91° and extension 6.33°. Lateral flexion to both right and left side had very low LSD values of 0.42cm and 0.24cm respectively. Movement would have to change by this extent to indicate true change anything less than these measures would be due to measurement error. In comparison with the findings of others (Tables 4.3, p70A and 4.4, p72A) the results from this study are good with higher PPMCC for flexion and extension than any other author.

The CoV for flexion was 11.39%, which is barely adequate, but 40.98% for extension is outside clinically acceptable levels. The high CoV is a direct result of the large spread of data for the extension test retest differences, so to evaluate reliability the LSD must be assessed. The LSD for flexion (6.33°) and extension (4.91°) indicate that more than 6.3° of change has to take place for real change to occur. This may be judged as a clinically acceptable level in human measurement but is higher than preferred. The PPMCCs for lateral flexion are good, but the CoV are greater than those of Merritt et al, 1986 (Table 4.4, p 72A). The LSDs indicate that more than 4mm of change must take place for real difference to be seen, again this is acceptable clinically.

5.4.4.2 Hip data

Reliability of goniometry data when measuring the hip joint was high with LSD of between 3.87° to 2.43°, the largest variance occurred when measuring flexion and the least for extension (Table 5.10).

Pearson Product Moment Correlation Co-efficient (r) were again very good ranging from 0.85 to 0.94, $p<0.001$, with Adduction having the best relationship and extension the lowest but all were significant (Table 5.10). Comparison with the reliability values from other authors cannot be undertaken as there is no published research except that for hip rotation from Barbee Ellison et al (1990). As these

Table 5.11 Reliability of true leg length measures measured on 2 occasions

	Test 1	Test 2	Differences between tests (cm)	Mean of tests (cm)
1	89.5	89	0.5	89.25
2	87.5	87	0.5	87.25
3	94.5	94.5	0	94.5
4	83	83	0	83
5	91	90.5	0.5	90.75
6	80	80	0	80
Mean	87.58	87.33	0.25	87.46
SD	5.32	5.23	0.27	5.28

Table 5.12 Assessment of warm up drift at 10-minute intervals over 2 hours
Standard deviations of system output (N) taken at 10-minute intervals over 2 hours

Time intervals (minutes)	1st hour (N)	Time intervals (minutes)	2nd hour (N)
0	0.66		
10	0.72	70	0.67
20	0.7	80	0.63
30	0.68	90	0.60
40	0.74	100	0.59
50	0.76	110	0.61
60	0.73	120	0.58

authors used ICC direct comparisons cannot be made. For both lumbar spine and hip measurement there was excellent intra-rater reliability for all movements.

5.4.5 Reliability of true leg length measurements

The intra-tester measures of true leg lengths were undertaken on six healthy participants on two separate occasions. The dominant leg was ascertained for each participant, and the measurement from the Anterior Superior Iliac Spine to the inferior tip of the medial malleolus was identified by a standard tape measure (Beattie et al, 1990). Leg length measures were taken twice from each leg and the mean of these was recorded as per Gurney (2002). The overall mean for each set of data (Table 5.11) were very similar with a mean difference of 0.25 ±0.27 cm between the sets of results. There was a strong positive correlation ($r= 0.99$, $p<0.0001$) between the data sets and the LSD was 0.69 cm (Appendix D). These results indicate that there is very good intra-rater reliability for true leg length measurements.

These results correspond to those of others including Beattie et al, 1990; Hoyle et al (1991) who found intra-rater to be high on repeated tests ($p<0.001$). Gurney (2002) suggests that the tape measure technique from ASIS to medial malleolus is acceptable as a screening tool. The validity of this measure is much debated but as the intra-rater reliability in this pilot study was high, with a low LSD value, the measure was accepted for use in this study.

5.5 FORCE PLATE VERIFICATION

Several tests were undertaken to assess the accuracy, precision and capability of the Bertec 600*400 strain gauge force platform. All data was collected at 300Hz unless otherwise stated as this represents the frequency commonly used in literature and that used in the current study.

Table 5.13 Variation of system output (N) taken at 10-minute intervals over 2 hours

Time intervals (minutes)	1st hour (N)	Time intervals (minutes)	2nd hour (N)
0	2.9		
10	2.9	70	1.5
20	2.7	80	1.6
30	2.6	90	1.7
40	2.5	100	1.6
50	2.5	110	1.7
60	2.6	120	1.6

Table 5.14 Force plate drift with time, Standard deviation of the system output (N) over the 20 minutes

Mass Applied	System Output (N)
0 kg	0.97
20 kg	1
30 kg	1.3

Table 5.15 Estimation of horizontal force, comparison of spring balance and force plate data (N) in the X and Y direction, mean (SD).

	Spring balance calculations	Force plate Measurement
Fx (N)	29 (2.0)	27.5 (2.12)
Mz (Nm)	7.4 (0.5)	6.9 (0.42)
Fy (N)	29 (2.0)	28 (1.41)
Mz (Nm)	4.4 (0.3)	4.4 (0.14)

5.5.1 Warm up drift

To test the effect of warm up time on the system response, the system was switched on and zeroed and a 60sec test was recorded every 10 minutes for two hours (Table 5.12 (p129A) & 5.13. The system was re-zeroed after 60 minutes as it was estimated that data collection would normally only take one hour. There was no weight on the platform. The standard deviation and range of output from the first hour was larger than those of the second hour. The maximum error in range was 2.9N in the first hour and 1.7N in the second (Table 5.13). The system output was therefore less stable during the first hour than the second, indicating that for all subsequent testing the force platform should be switched on at least one hour prior to data collection.

5.5.2 Drift with time

The measurement of function requires that data be collected over a continuous period. To assess the system output during continuous data collection, data was collected for 20 minutes, the maximum time for a test on the force plate during this study. Drift was assessed unloaded and with a 20 and then 30kg weight applied. The frequency of the system was reduced to 1Hz to allow the system to record for this length of time. The standard deviation of the system output over 20 minutes (Table 5.14) indicated that with increased weight the drift increased respectively but that 95% of the output over the period was less than 2N.

5.5.3 Estimation of vertical force (Fz)

To test the estimation of vertical force a single subject with body mass (67kg, i.e. 657N) stood on the force plate for one second, and data was recorded at 100Hz. The mean output from the system over this period was 652±-3.2N which is less than a 10% difference between the readings. This procedure was then repeated 10 times with a mean difference of 4.3±1.34 giving a percentage difference of 0.65% and a LSD of 3.03 N, indicating comparable repeated readings for vertical force (Fz).

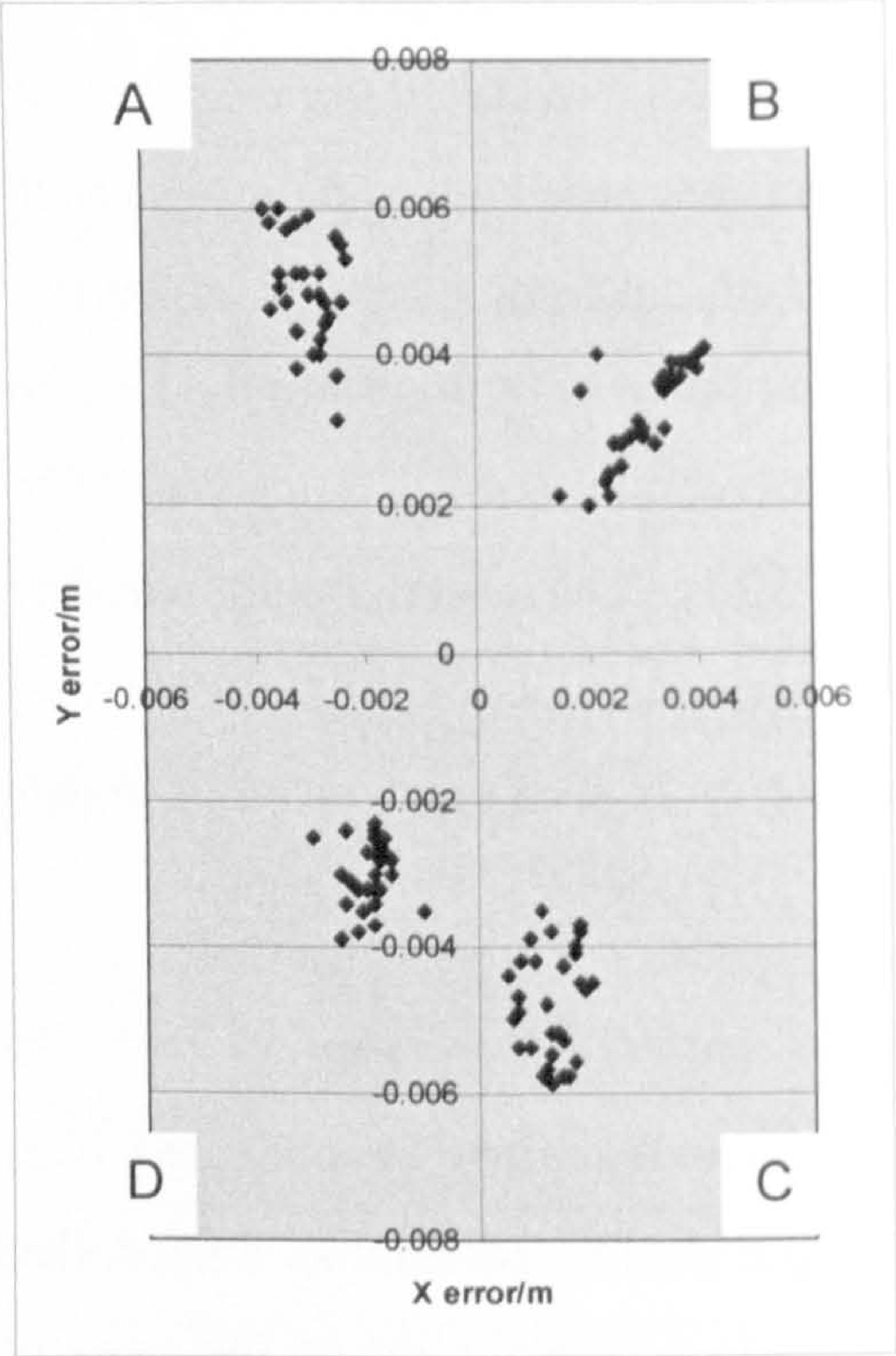


Figure 5.5 Position errors from 4 points on force plate (m)

Table 5.16 Measurement of static position loading of force platform, mean absolute error and range of error, 40 repeated tests at each point.

	Mean absolute error (m)		Range(mm)	
	X	Y	X	Y
A	0.0009	0.001	1.5	2.9
B	0.0009	0.0007	2.6	2.1
C	0.0009	0.0007	1.2	2.9
D	0.002	0.001	2	1.6

Table 5.17 Precision measurements of static loading of force platform, (standard deviation of the error over 40 repeated tests at each point (m))

	X direction	Y direction
A	0.0004	0.001
B	0.001	0.001
C	0.0006	0.0006
D	0.0003	0.0004

5.5.4 Estimation of horizontal force

As there was only limited space in the force plate pit full testing of the force plate's ability to measure in the x and y directions could not be undertaken.

A spring balance was tied to a piece of string, which was wrapped around the force plate. The spring balance was held as level as possible and a known load (Fx or Fy) was applied in the x and y direction. The applied Mz could be calculated from the known Fx or Fy, and x or y. Typical output values were then compared with the known input values. The maximum load that could be applied within the restricted force plate pit was 3±0.2kgf (spring balance), i.e. 29±2N. This was a small force so the gains were therefore turned up to 100. Data was collected 10 times, for 30s at a sampling rate of 100Hz and the mean findings indicate no difference between the two sets of data (Table 5.15, p130A). The greatest difference was for the Fx value.

5.5.5 Static position loading

Four static positions were tested on the force platform, by pressing the end of a stick (5mm in diameter) onto four points on the force plate equidistant from the centre of the plate:

Position	X (m)	Y (m)	Position	X (m)	Y (m)
A	-0.4	0.4	C	0.4	-0.4
B	0.4	0.4	D	-0.4	-0.4

Each point was tested 40 times and the positional errors were recorded onto a graph (Figure 5.5). The maximal errors were less than 6mm in Y direction and 4mm in the X.

A mean absolute error of 1mm or less (Table 5.16) was found in each direction for each point with position D having the greatest mean absolute error of 2mm in X direction and 1mm in Y. Point B had the largest error range.

To assess the precision of the repeated positional tests the standard deviation of the error was ascertained (Table 5.17). The least precise measures were in position B, 1mm in both the X and Y direction. The other positions all showed greater precision with standard deviations of less than 0.6mm.

6.0 METHOD – Test protocol

6.1 SELECTION OF PATIENTS WITH TOTAL HIP REPLACEMENTS

Volunteers for the group with total hip replacements were recruited first to ascertain the number of possible participants and to assess age, gender and activity level so that group matching could take place with the 'normal' population.

Patients with a primary total hip replacement were identified from the admission lists for two hospitals in the local area. One hospital was NHS and one private but the same surgeon, using the same operative procedure operated on all patients. The names from the admission lists for the last three years were obtained from the orthopaedic admissions staff and anyone with the criteria listed in section 6.1.1 was sent a letter inviting them to enter the study (Appendix E). Participants contacted the researcher by telephone if they agreed to take part in the study or if they had any questions. A total of 79 people (64 females & 15 males) were contacted in three separate trawls with 46 people (58.2%) replying positively and 33 did not reply. Of the 46 people replying, 26 (56.52%) were able to attend for assessment, representing 32.9% of the original number of people contacted of the repliers and 20 repliers could not attend. The ratio of males to females having had surgery was 1: 4.3. A list of the names and addresses of all participants was sent to the orthopaedic consultant involved as well as any up to date information which had been supplied by any of the participants whether they attended for testing or not.

A convenient appointment time was arranged and a letter was sent confirming time, date and place giving details of transport and contact numbers of the researcher (Appendix F). An information sheet describing the study was also included with the appointment confirmation (Appendix G(a)).

6.1.1 Inclusion criteria

Participants were included in the contact list if they:

- were aged 65 or over
- had primary total hip replacement at least two years previously
- had regained full independence post-operation
- had no excessive pain around the joint replacement limiting activity
- had no post-operative complications or extra surgical procedures e.g. acetabulum reinforcement
- had no revision replacement surgery
- had no injury or disease to any other lower limb joint in the last year
- had no back pain which limited everyday activities in last year
- had no serious balance or co-ordination problems affecting everyday function
- had full vision with or without glasses
- were happy to undress to shorts and sleeveless top in the laboratory situation
- gave full consent to measurement

6.1.2 Operative procedure

All participants had a Stanmore total hip replacement using a posterolateral incision. The greater trochanter was not removed and any soft tissue damage was repaired. All patients had a general anaesthetic and painkillers were given as required. The post-operative regime required that patients had a drain in situ for two days, were mobilised on the second post-operative day and they were allowed to sit for a short time from this point.

Patients, on average, stayed in hospital for seven days but all patients in the private hospital were discharged by day five. All patients left hospital walking with one or two sticks and were able to climb a single step.

Fifty percent of the THR participants had contact with a physiotherapist and the 10 patients from the private hospital were given written exercise sheets to follow.

6.2 SELECTION OF PARTICIPANTS FOR NON-TOTAL HIP REPLACEMENT GROUP

Participants were asked to volunteer to join the study via advertising posters and personal communication at two local 'elderberry' groups. The elderberries are a social and exercise group for over 55 year olds in the East London area who meet three times a week. Members of the group take part in a number of sports or exercises including badminton, swimming, keep fit, walking etc. as well as social outings and gatherings.

An invitation letter was sent to all volunteers giving information about the study and the tasks involved (Appendix G(b)). If the volunteers were happy with the test procedures they contacted the researcher and an appointment time was arranged. As per the previous group a confirmation letter was sent to them (Appendix F).

Participants were included in the study if they met the criteria of:

- Aged 65 or over
- No injury or disease to any lower limb joints in the last year
- No serious balance or co-ordination problems
- No back pain which limited function or movement in last year
- Generally fit
- Full vision with or without glasses
- Were happy to undress to shorts and sleeveless top in the laboratory situation
- Gave full consent to measurement

6.3 ETHICS AND CONSENT

Full ethical approval was obtained from the University of East London ethics committee. The orthopaedic consultant who undertook all the operative procedures gave written consent for the patients to be contacted (see Appendix H) but hospital ethics approval was not required as the patients had left the immediate care of the hospitals concerned. A copy of the study protocol and invitation letter was sent to the hospital ethics committee to inform them of the study details.

Flowchart of study protocol:

1. Participants gave agreement to enter the study

2. Study protocol discussed and consent forms completed

3. *Height, Weight and anthropometric data collected & general questions asked*

4. *Passive Physiological Measurement undertaken.*

Random allocation of the order of measurement for hip and lumbar spine movement.

5. *Three-dimensional static measurement in standing and sitting were taken for hip, knee, ankle and lumbar spine positions*

6. *Three-dimensional dynamic measurement of hip, pelvis and lumbar spine movement during gait, sitting to standing, bending forward in sitting and standing.*

Random allocation of functions, measurement undertaken with the Kinemetrix Motion Analysis System and a single Bertec Force plate

Table 6.1 Marker position for hip and lumbar spine testing

Hip Markers	**Lumbar Spine markers**
Acromion Process	Acromion
ASIS Left	3 Thoracic spine markers
ASIS Right	3 Lumbar spine markers
S_2 – middle marker of lumbar spine markers	(Use same S_2 marker for both measurements)
Greater trochanter	
Anterior Thigh	
Lateral Femoral Condyle	
Anterior Shin	
Lateral Malleolus	
5th Metatarsal	

Written informed consent was obtained from all participants prior to them taking part in the study (Appendix I) after they had read the information letter (Appendix G (a or b)) and discussed any issues arising. The written consent form followed the format dictated by the University ethics committee at that time. Participants were reassured that they could withdraw from the study at any time.

6.4 TEST PROTOCOL

Prior to testing the Kinemetric system was calibrated according to the manufacturers instructions using the calibration frame; a three-dimensional cube with nine, 25mm marker set in known positions on three aspects of the cube. The camera focus was also tested using the frame for reference. The Bertec strain gauge force platform was switched on and allowed to warm up for 60 minutes prior to testing. The amplifier for the force platform was 'zeroed' once warm up was complete, prior to data collection and between every set of measurements taken.

On entering the laboratory the participants were shown the room and facilities to be used and the procedure was explained. The flow chart of the study protocol can been seen on p135A.

Once all the paper work had been undertaken the participant was asked to change into a pair of running shorts which had been modified to allow the Greater Trochanter, ASIS and PSIS to be palpated. Female participants wore a short sleeveless top and males had a bare chest. All subjects had bare feet. A general health questionnaire was completed and information about their THR (if applicable) was ascertained (Appendix J). After height and weight were taken, the bony landmarks listed below (Table 6.1) were identified in standing using the guidelines established in the laboratory and marked with contrasting skin colour pen, to ensure marker replacement could be undertaken.

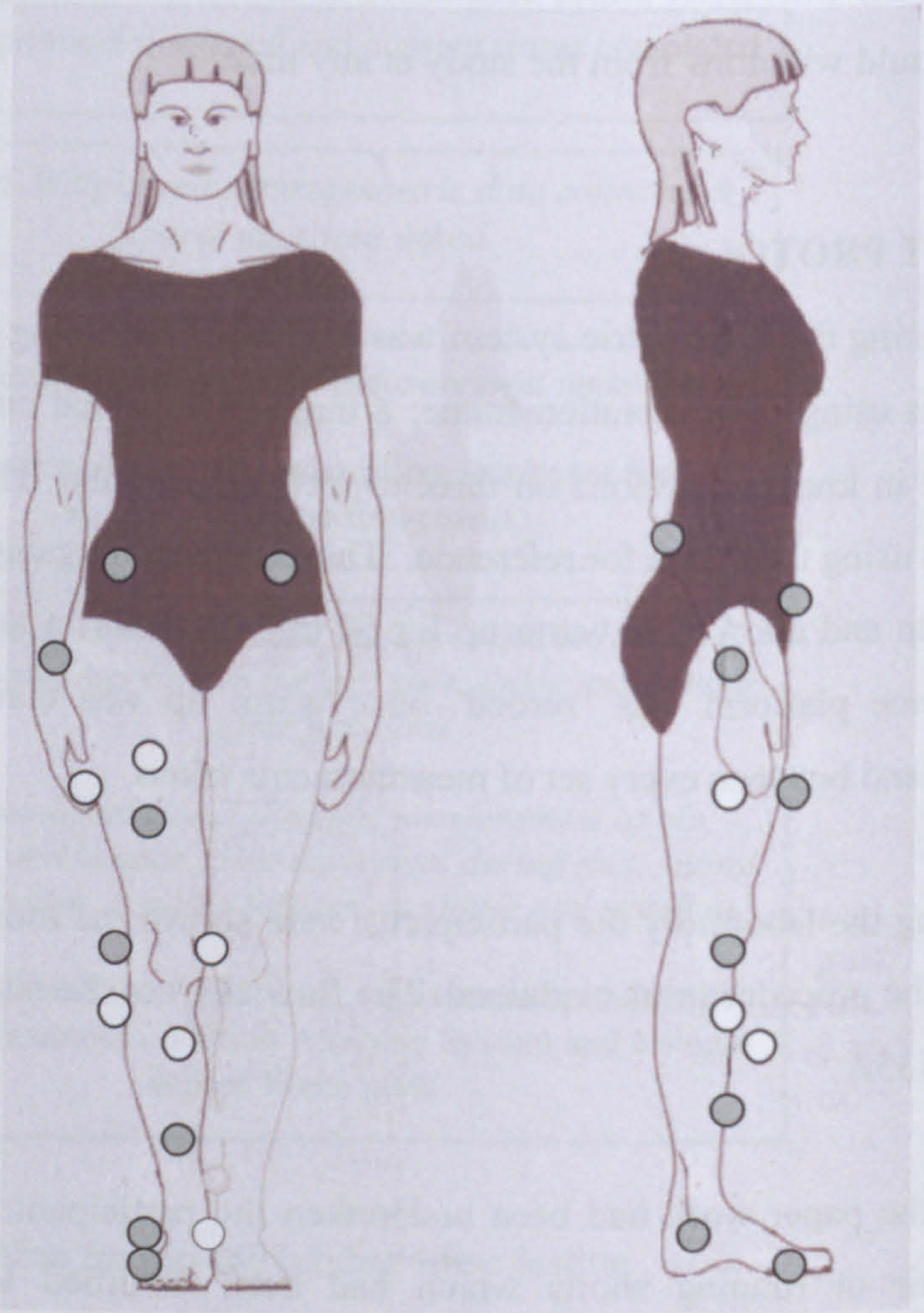


Figure 6.1 Marker Placement: Lower limb markers
Static marker testing: white markers,
Grey markers used for lower limb data collection

6.4.1. Bony landmark identification:

6.4.1.1 Lumbar spine landmarks

Identification of lumbar spinous processes by the method outlined by Burton (1986) and Hindle et al (1990). The spinous process of S_2 was identified by palpating the PSIS in the sacral dimples and then moving the hands to the central mid point between the two. This was marked with an indelible pen at the S_2 level. From the top of iliac crests the hands were moved centrally to the mid point to identify L_4 then the spinous processes were counted caudally until the T_{12} spinous process was identified. This was confirmed by palpating the lowest rib on each rib, moving the hands centrally to identify the spinous process of T_{12}. This point was then marked as above.

6.4.1.2 Lower limb landmarks

The lower limb bony landmarks were applied in accordance with the normal laboratory procedures and were:

- Lateral aspect fifth metatarsophalangeal,
- Inferior tip of lateral malleolus,
- Anterior shank of tibia (56.7% of segment length away from distal end) at 90° to LE and GRT,
- Lateral epicondyle of the femur (LE),
- Anterior aspect of thigh (58.7% of segment length away from distal end) at 90° to LE and GRT,
- Inferior tip of the Greater Trochanter(GT),
- Anterior superior iliac spines (ASIS),
- Lateral tip of the acromion processes (Figure 6.1)

Additional markers were identified for static recognition of underlying bony segment and axes, prior to dynamic testing these included: Right and Left medial and lateral femoral epicondyles, right and left medial malleoli. These landmarks were removed after static testing.

6.4.2 Anthropometric data

Prior to attachment of the markers the anthropometric data were gathered for calculation of limb segments and joint centres. The anthropometric form can be seen in Appendix K. True and apparent leg length measurements were taken. True length

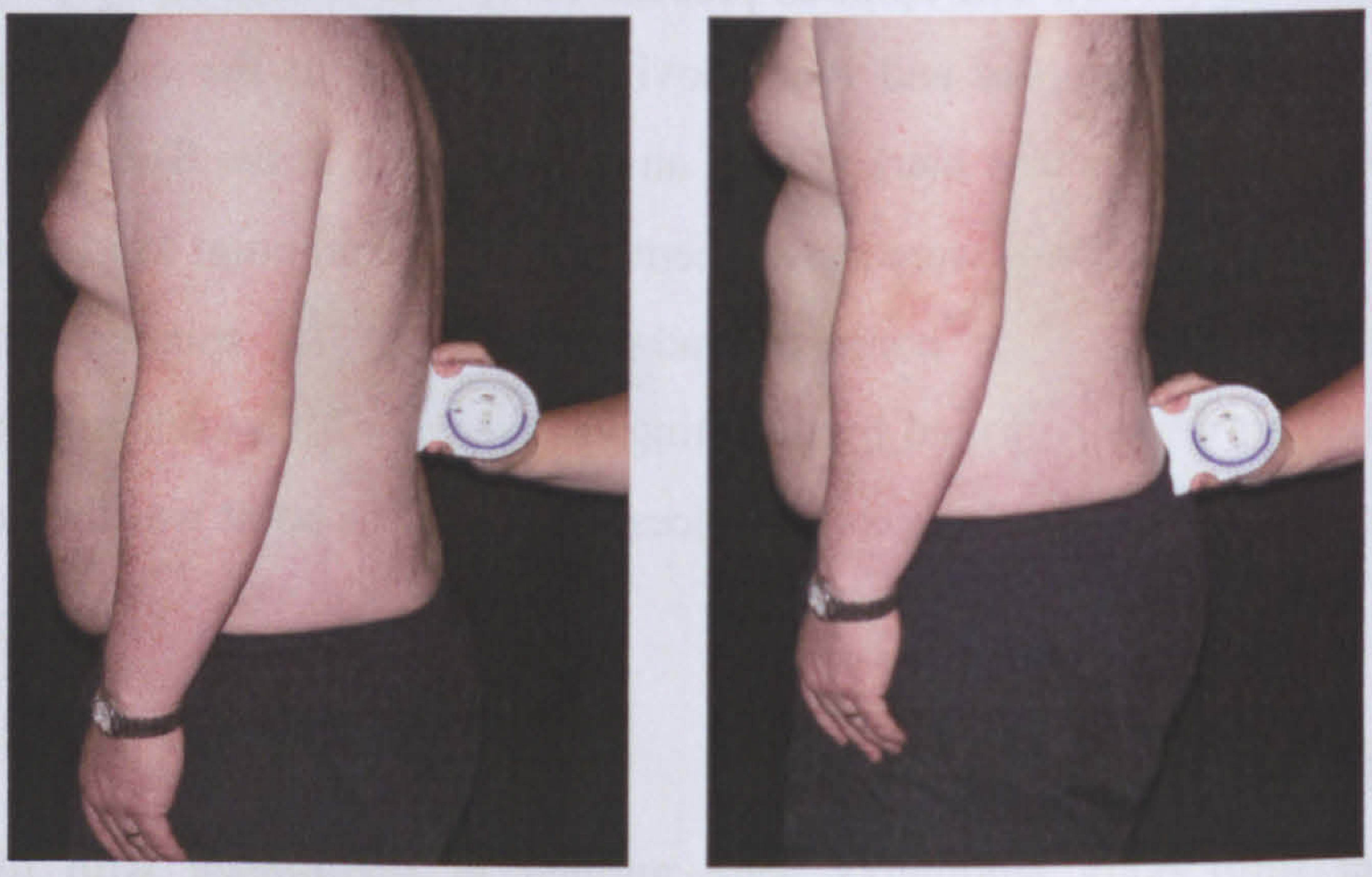


Figure 6.2 Lumbar spine measurement: Erect standing

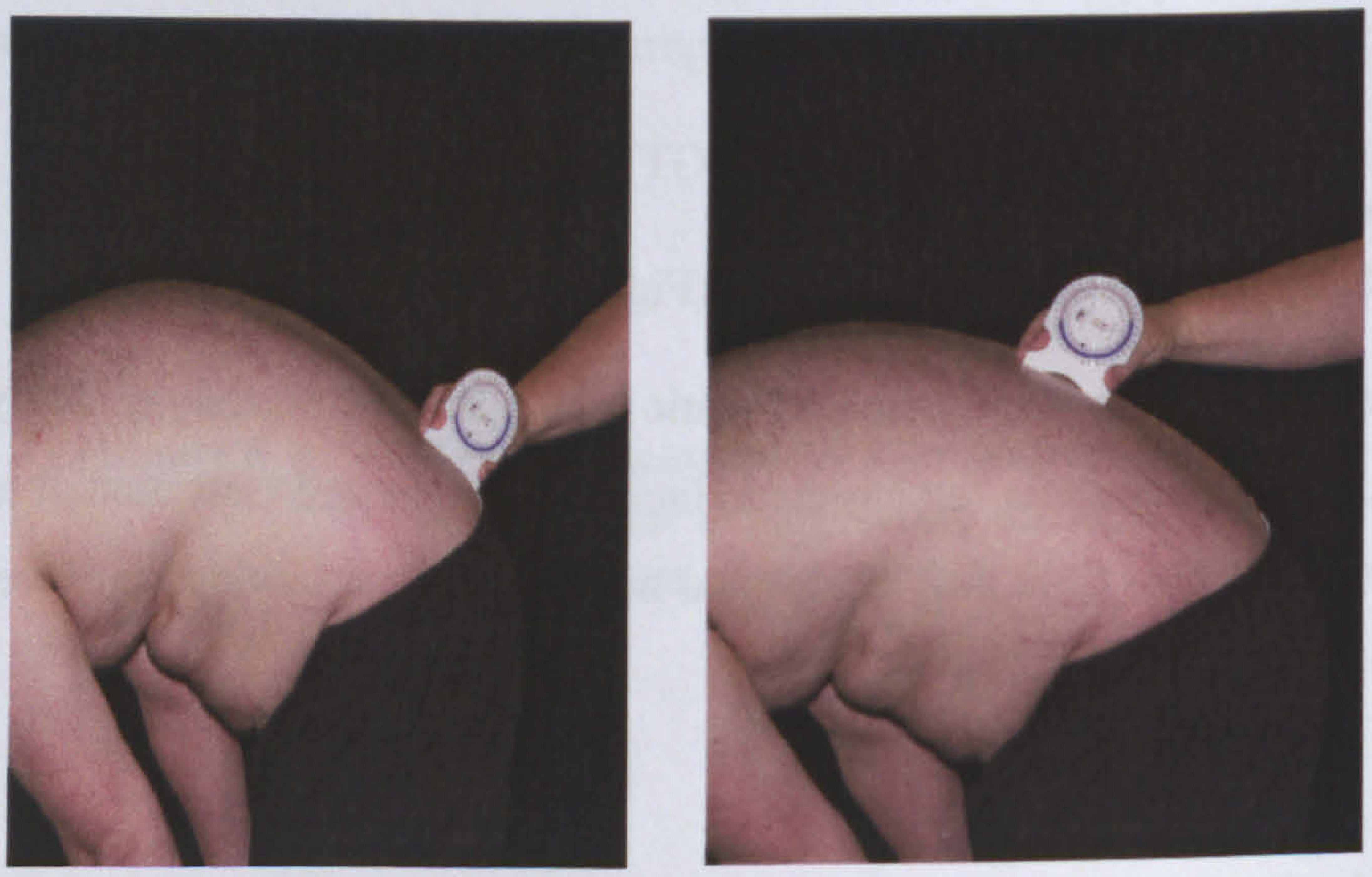


Figure 6.3 Lumbar spine measurement: flexion

was measured using the method outlined in the reliability study in section 5.4.5. Apparent leg length was measured from the lower edge of the Xyphoid sternum to the inferior tip of the medial malleolus and the mean of two readings was recorded for each leg for each measurement.

6.4.3 Passive Physiological Data collection procedure

A random allocation of passive physiological data collection procedure was undertaken prior to data collection. Once the landmarks had been identified the participant was asked to stand in their natural standing posture with feet approximately 20 cm apart, look straight ahead at a point on the wall at eye level, with their hands hanging loosely at their sides. This standardised standing position was used and suggested by Merritt et al (1986a), Roberts et al (1989) and Newton and Waddell (1991) for measuring sagittal lumbar flexion and extension. Five warm ups and stretches were undertaken prior to testing in each direction. Lumbar spine position in erect standing was taken as a baseline prior to flexion and extension (Figure 6.2).

6.4.3.1 Lumbar Flexion

Lumbar flexion was measured with the clinical goniometer by recording the position of the S_2 and T_{12}. Participants were then instructed to bend forward reaching as far as possible, without causing pain. While the participants were fully flexed measurements were re-taken at S_2 and T_{12}. The difference in values from S_2 and T_{12} measurement gave a value for the lumbar curvature at the start and end of flexion and subtraction of the data from the 2nd to the 1st curvature data sets gave the degree of forward flexion. Movements were repeated three times. The inclinometer was zeroed prior to placing it on the spinous processes to take the measurement. (Figure 6.3)

6.4.3.2 Lumbar Extension

Extension of the lumbar spine was measured using the same skin marks. Participants were instructed to lean backward as far as possible, looking up to the ceiling. The subject's hands were placed on the lower back to assure a stable position and to minimise the motion of the pelvis (Weisl, 1955) movements were repeated three

Figure 6.4 Lumbar spine measurement: extension:

Figure 6.5 Lumbar spine measurement: Lateral Flexion

times. The difference in values from S_2 and T_{12} measurement gave a value for the lumbar curvature at the start and end of extension and subtraction of the data from the 2nd to the 1st curvature data sets gave the degree of extension. The inclinometer was always zeroed prior to placing it on the spinous processes to take measurements, all measurements were in degrees. (Figure 6.4)

Using the starting posture prior to flexion and then extension the standing posture of the lumbar spine could also be assessed for differences between the groups.

6.4.3.3 Lateral Lumbar Flexion

For lateral flexion the participants stood with their back against a flat wall, to avoid either forward flexion and extension. With the arm straight, the position of their middle finger in erect standing was marked on the thigh and then the participants were asked to slide sideways down the wall as far as they could and the position on the middle finger was again marked on the thigh. The distance between the two marks gave the values for lateral flexion (Figure 6.5). Both left and right lateral flexion was performed three times and all measurements were in centimetres.

6.4.3.4 Hip Measurements

Prior to these measurements the participant was asked to carry out three full stretches: bending forward and backwards in standing, rotating the lower limbs in standing and bending the knee and hip as far as possible in supine lying. Each of the hip movements was undertaken three times, recorded and the averages were calculated. All hip measurements were undertaken with a 360° universal goniometer following the guidelines outlined by Norkin & White (1995). Hip flexion, abduction and adduction, and rotation were all measured in supine lying, extension in prone lying or in supine via the Thomas test (Norkin & White, 1995) if prone lying was not possible, as recommended by Bartlett et al (1985).

The participants were given a rest after the passive physiological measurements and offered refreshment and a comfort break.

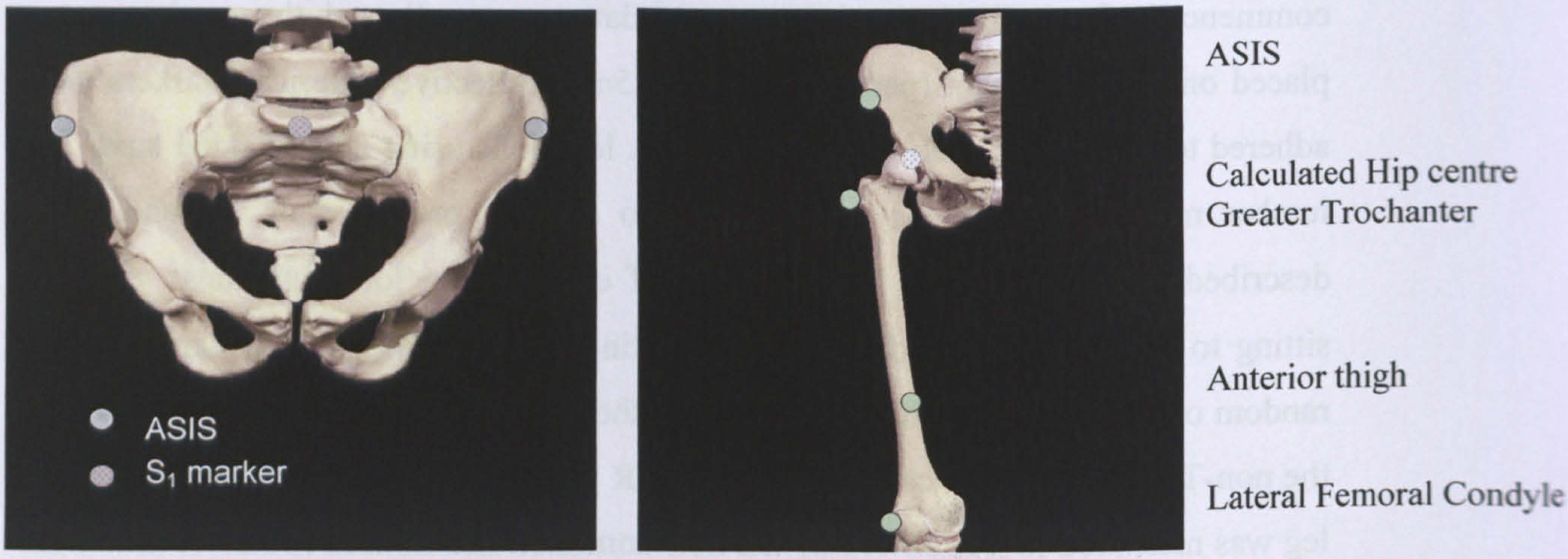
6.4.4 Kinematic and kinetic data collection procedure

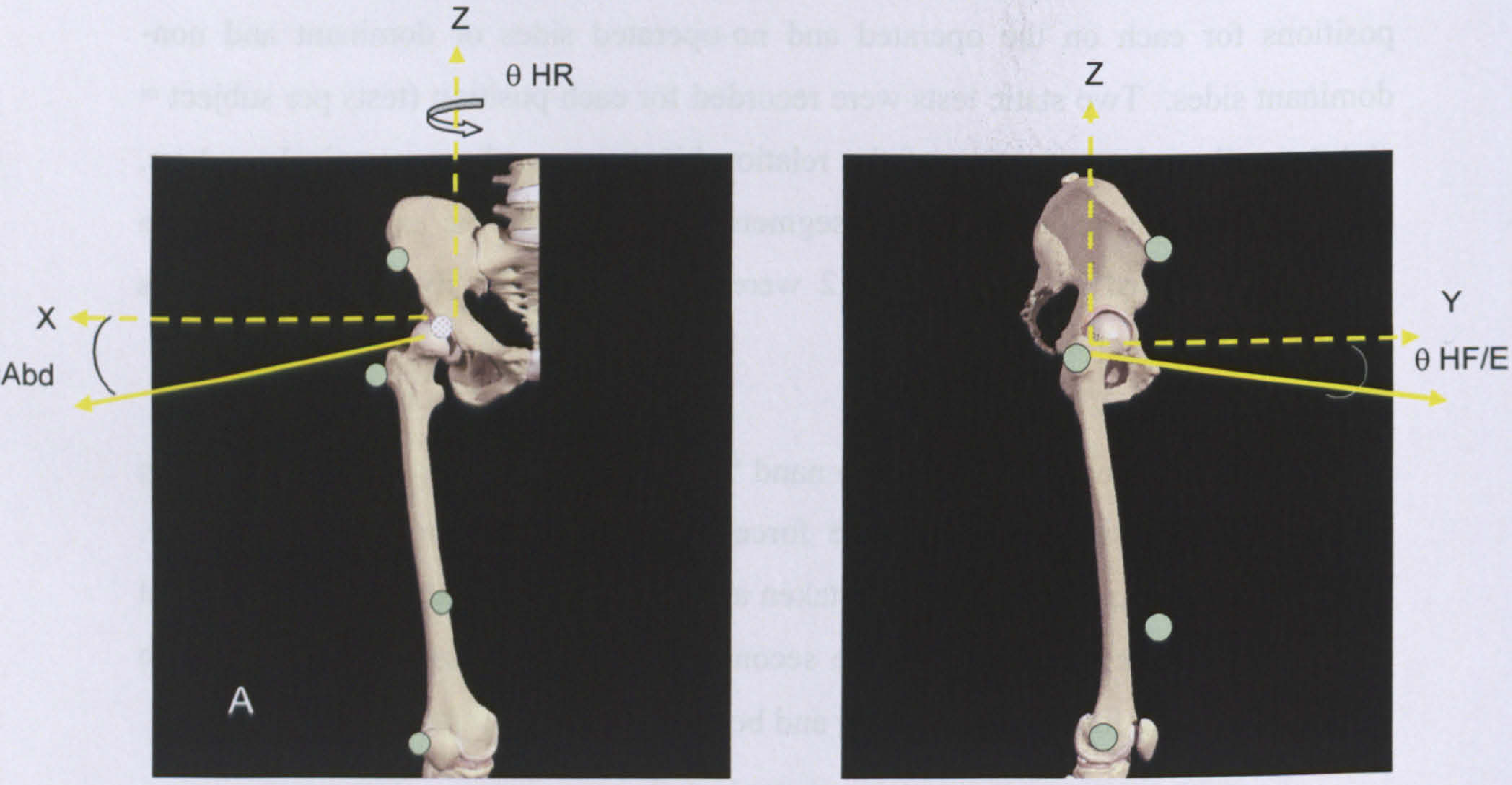
All participants were cleared for allergies to sticky tape prior to data collection commenced. Once all the anthropometric data were collected the markers were placed on the participant (per section 6.4). 25mm reflective spherical markers were adhered to the subject's skin on the pen mark locations using double sided tape. The lumbar measurement plates were applied to spinous processes of T_{12} and S_2 as described in section 5.2.2. Measurement of each of the four functions: walking, sitting to standing and bending forward (sitting and standing) was undertaken in a random order for each participant, firstly for the lumbar spine and THR side and then the non-THR side. In the case of the non-THR group the lumbar spine and dominant leg was measured first followed by the non-dominant and lumbar spine. A minimum of five tests per function were undertaken, with the aim of achieving three good tests per participant. Static positional data was collected in both the standing and sitting positions for each on the operated and no-operated sides or dominant and non-dominant sides. Two static tests were recorded for each position (tests per subject = eight) to allow determination of the relationship between the anatomical markers, and corresponding underlying bony segments and the dynamic axes. Some of the markers mentioned in section 6.4.1.2 were removed before dynamic testing was undertaken.

All recording commenced on the command '*Are you ready, three, two, one, go*' with the motion analysis system and the force plate being triggered simultaneously. Kinemetrix data collection was undertaken at 50Hz and force plate data collection at 300Hz. Movement stopped after five seconds for gait, three seconds for sitting to standing, bending forward in standing and bending forward in sitting.

Walking:
A single 25mm reflective marker was placed on the floor in the field of view of the cameras but out of the walking path, so that the cameras started recording prior to the participant being in the field of view.

Pelvic markers for calculation of hip movement Thigh markers for calculation of hip movement





Hip angles under consideration: Angles measured from the identification of the hip joint centre calculated from the position of the markers on the pelvis and then by the relative movement of these markers to the movement of the thigh markers

A Hip Rotation (θ HR) Horizontal Plane; Hip Abduction (θ HAbd) Frontal Plane;
B Hip Flexion/ Extension (θ HF/E) Sagittal Plane

(Pictures from Primal Pictures (Site accessed 16.02.08)
https://auth.athensams.net/?ath_returl=%22http://www.anatomy.tv/%22&ath_dspid=PRIMAL.atv)

With the participant standing just outside the camera field, the participant was asked to walk at normal relaxed pace, with the foot of the side being measured striking the centre of the force platform. The arms were held lightly across the chest to ensure that all reflective markers could be seen. The participant had as many warm up sessions as needed until they felt comfortable and a good foot strike on the force platform was achieved. Once five tests had been collected the participant sat on the stool ready for the next function.

Sit to stand:

With the adjustable stool placed at a height which allowed a starting position of 70° of hip flexion, the participant sat with the foot of the side being measured on the forceplatform. The participant was asked to rise in their own time from the erect sitting position into the standing position. The arms were held lightly across the chest. This position was then held, before returning to the sitting position. As the participants could not use their hands for this test the warm up trials allowed practise at sitting without feeling for the stool. Once the participant felt comfortable, five data sets were collected.

Bending Forward:

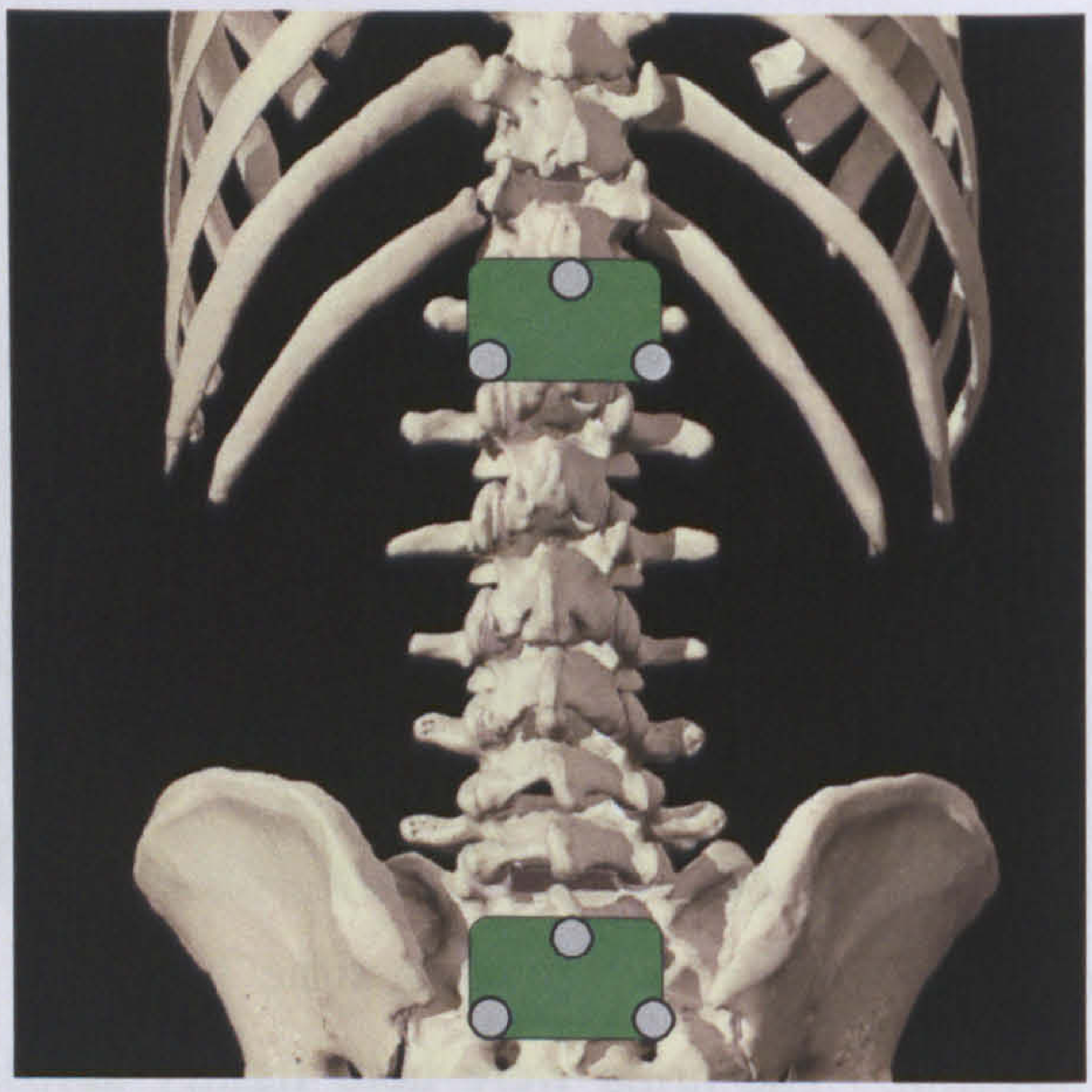
Sitting:

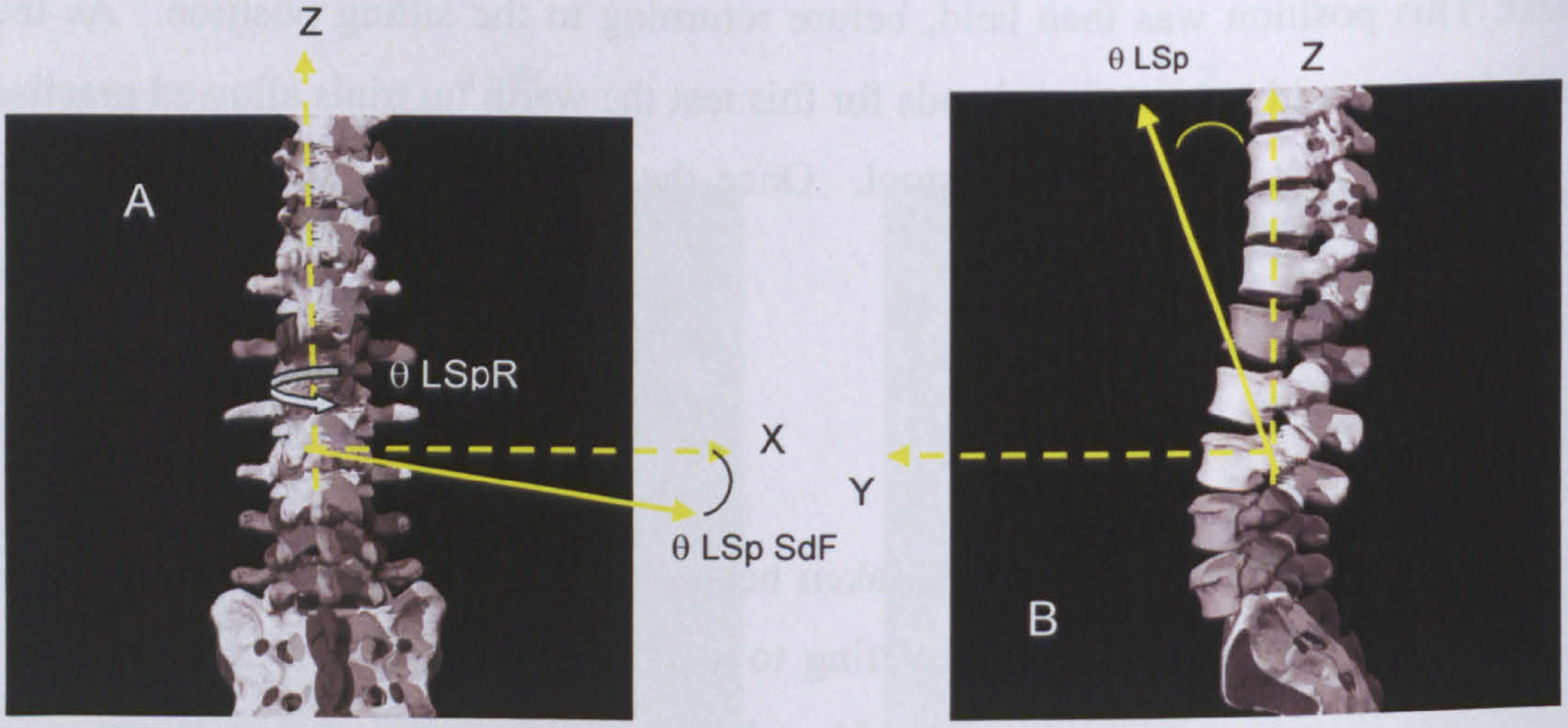
Three warm-up stretches were undertaken before the data sets were collected. From the sitting position, as outlined in sitting to standing, the participant was asked to place their hands together and reach down between their legs as far as possible. If they could touch the floor they did so. Once again the foot of the side being measured was placed on the force plate. No data was collected during the return to the erect sitting position.

Standing:

From the erect standing position the subject bent forward as far as they could with the hands placed together and moving centrally down the body. The arms and knees were kept straight during the movement and if any pain or discomfort was experienced then the participant stopped the movement. When the end point (pain or

Lumbar Spine markers for calculation of Lumbar spine movement





Lumbar Spine angles under consideration: Angles were derived from the relative change in motion of the three markers at S_2 (pelvis) to those at L_1 (Thoraco-lumbar junction).
A Lumbar Spine Rotation (θ LSpR); Lumbar Spine Side Flexion (θ LSp SdF);
B Lumbar Spine Flexion/ Extension (θ LSp F/E)

Convention for Pelvic movement presented on page 175A

(Pictures from Primal Pictures (Site accessed 16.02.08)
https://auth.athensams.net/?ath_returl=%22http://www.anatomy.tv/%22&ath_dspid=PRIMAL.atv)

tightness in the posterior knee or thigh) was reached the participant remained in that position for a short while and then returned to erect standing. Three warm-up stretches were undertaken before five data sets were collected. No measurements were taken during the movement from the bent position to erect standing.

For all functions the participant dictated the pace of the movement at all times. Any pain, discomfort or issue occurring during the movement was noted and recorded on the measurement sheets. All data was digitised in the Kinemetrix software package to ensure complete data sets on three occasions for each of the participants. The Kinemetrix raw files were saved and then transferred into ASCII files for import into the Vicon software (Workstation).

6.5 ANALYSIS PROGRAM

Conventions for calculation of hip and lumbar spine angles can be found on pages 140A and 141A. Conventions for the pelvis can be found on page 175A. Details of the development of the analysis programs have been given in the method section 5.3.1, p115, a complete version of the each of the programs is provided in Appendix C, with a diagram of the axes of movement for the hip, lumbar spine and pelvis..

6.6 DATA ANALYSIS AND STATISTICS

Once the physiological and biomechanical data had been processed through the relative computer programs it was downloaded into Microsoft Office Excel 2003, and the Statistical Package for Social Sciences (SPSS) (version 10.1, September 2000) and descriptive and statistical analysis was applied.

6.6.1 Demographic and passive physiological data

To help decide which statistical analysis test were to be used all demographic and passive physiological data was tested for normality and uniformity, firstly by comparison with research from others using 95% confidence intervals and then by the Shapiro-Wilk test. Histograms with normal curve function of 'goodness of fit'

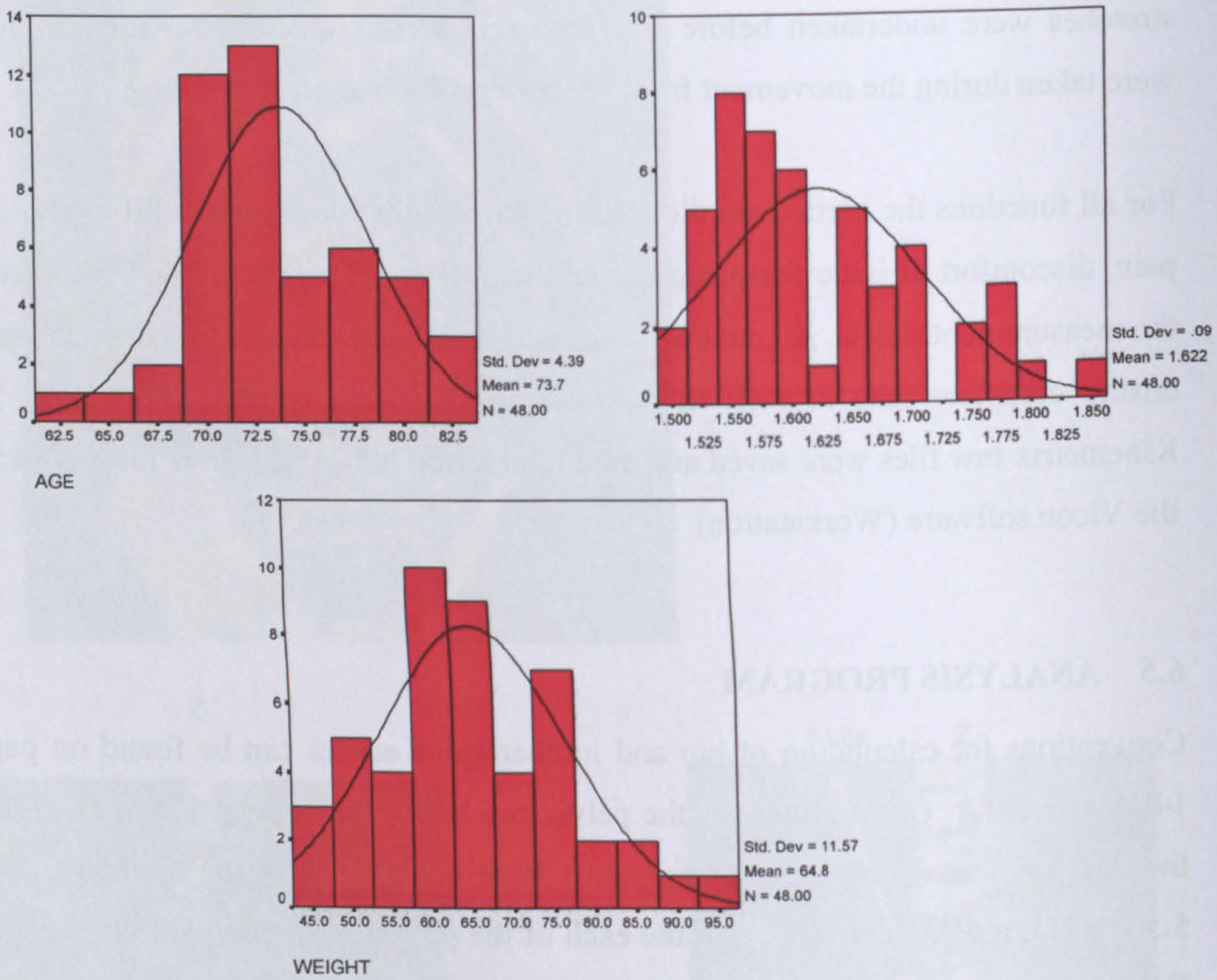


Figure 6.6 Normal Distribution demographic data.
Full details can be found in Appendix L

test were created for each data set using SPSS statistical package. The full data for the Shapiro-Wilk tests for normal distribution of demographic and physiological passive movement for can be found in Appendix L. The variables not having normal distribution are presented in histogram form and box plots of the median, 95% confidence intervals, and outliers, are given to demonstrate uniformity in Figures 6.6 – 6.8 (p142A - 143A) and Appendix L.

All demographic data were normally distributed and on the whole the physiological data was distributed normally. The data for extension and adduction in the THR group were not distributed normally, with hip extension mainly being 0° for the THR group and the adduction data was split evenly between those with 30° or more and those below, thus not giving a normal distribution. Data for knee movement were also not distributed normally for the THR group knee flexion and in both groups for knee extension. Normal distribution cannot be achieved for knee extension, as there is a ceiling effect at 0°, as the knee does not normally extend beyond this. THR knee flexion has a wide range of data with a greater number of lower values to the mean than greater, hence the lack of uniformity (Appendix L).

All the physiological data for the lumbar spine was normally distributed. As there were only 24 data sets for lumbar spine flexion and extension for both groups it is likely that larger numbers of data are needed to attain uniformity.

> *"In the past, the goodness of fit test was used to satisfy the underlying assumption of normality for parametric statistical test, however as statisticians have established that these tests, t-test and ANOVA, are robust to violations of normality, the goodness of fit test is now generally considered unnecessary for this purpose."* (Portney & Watkins,1993, p 489)

Given that the majority of the data was distributed normally, parametric analysis was undertaken in analysis of the lumbar spine, hip and knee. The quote above indicates that both the student t-test and ANOVA can be undertaken when there is not a complete or true normal distribution.

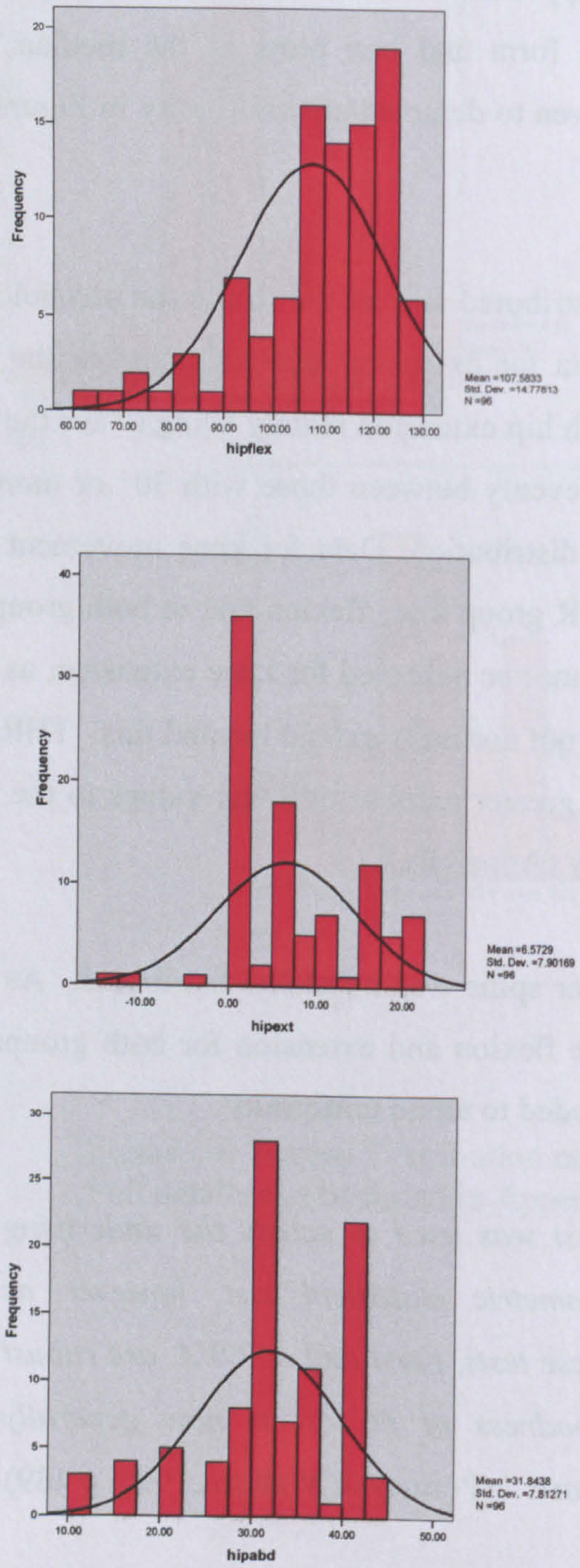


Figure 6.7 Normal Distribution of physiological data from hip – examples of movements.

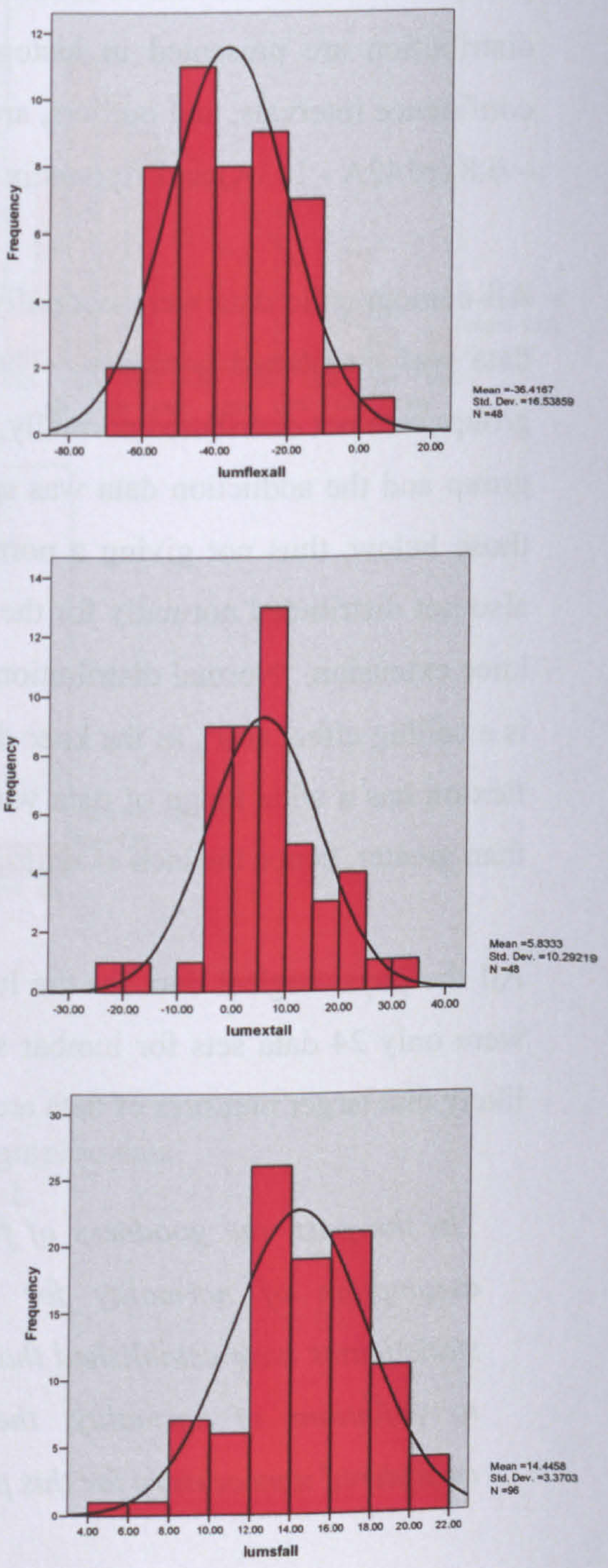


Figure 6.8 Normal Distribution of physiological data from Lumbar spine – examples of movements

Full details can be found in Appendix L

A two-factor repeated measures Analysis of Variance (ANOVA) was used when the data are classified in two ways e.g. study group (THR and non-THR) and side (left or right), when repeated measures from the sample participants were used. As there are 24 participants per group a balanced design was applied to the data. This test was used to assess the variance between sides and groups in all hip and knee and lateral lumbar spine physiological data.

When two groups of participants are compared for one variable only, a student t-test was undertaken, in particular the comparison of demographic data or lumbar spine movement. The t-test compares the means of two sets of data, and indicates the degree of separation between the groups. There are two types of t-test the dependent or independent. When repeated measures or matched participants are used then to improve the degree of control over the variables a paired or dependent t-test is used and will determine if values associated with two experimental conditions are significantly different from each other. Tests of significance involving paired comparisons tend to be more powerful than independent tests e.g. right vs left.

The independent (unpaired) is used when groups are composed of independent set of participants, with no inherent relationship derived from repeated measures. The t-test is based on the assumption that data represent normal distribution, that participants have been randomly selected and assigned and that the variances of the two groups are relatively equal e.g. THR vs non-THR.

Both tests have been used in this study. When comparing the right and left data for physiological movements a paired t-test was used, but when comparisons between groups (THR vs non-THR) was undertaken then an independent t-test was used, as true matching has not taken place. Overall the groups had similar ranges and numbers for age and gender but a direct matching was not undertaken.

T-tests were also used for post hoc analysis of hip flexion, extension, abduction, adduction, rotations and lumbar lateral flexion when two-factor repeated measures ANOVA was significant and further analysis was needed to identify specific issues.

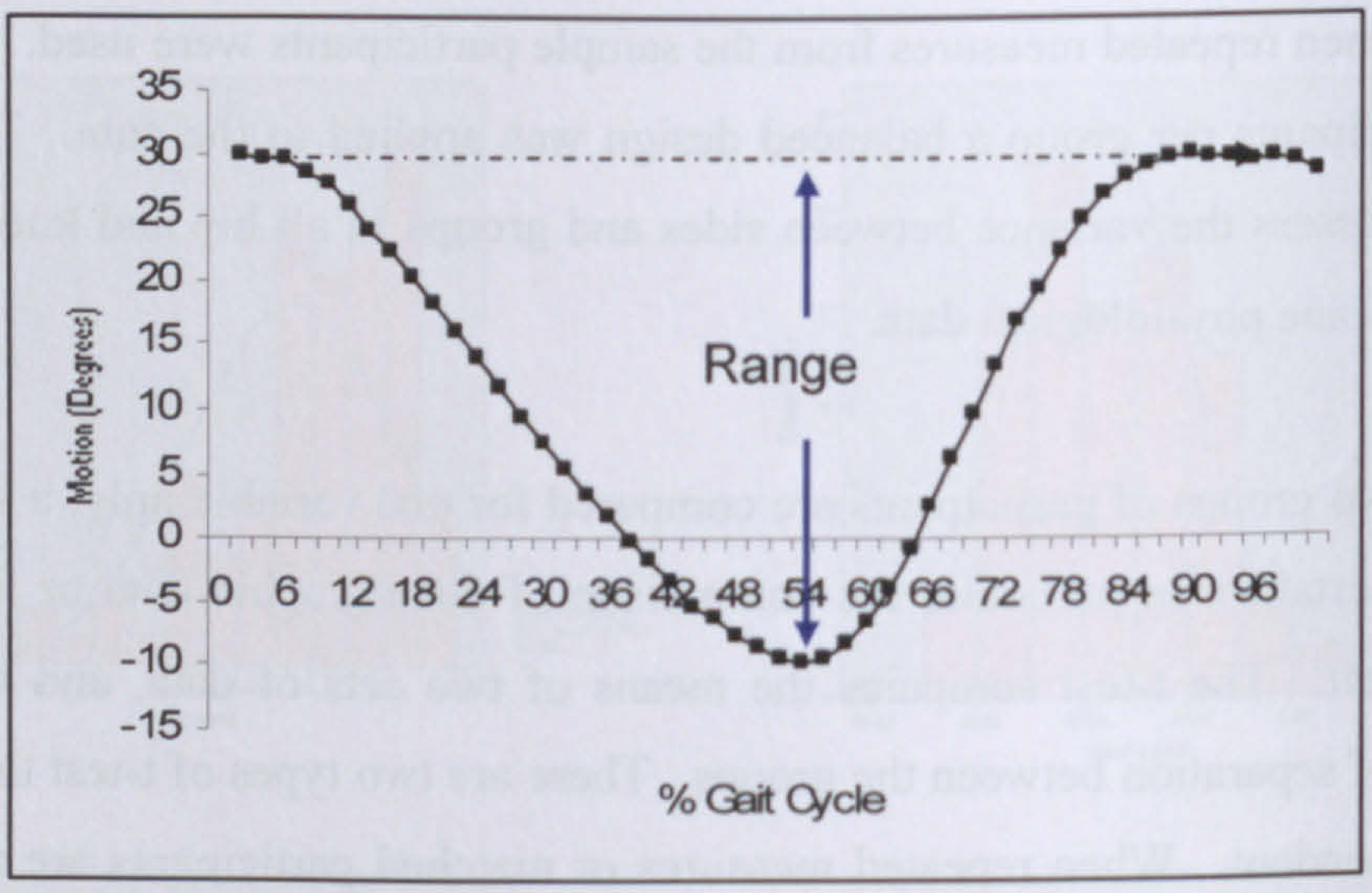


Figure 6.9 Calculation of range of movement through the gait cycle from maximum +ve value to maximum –ve value (Blue line).

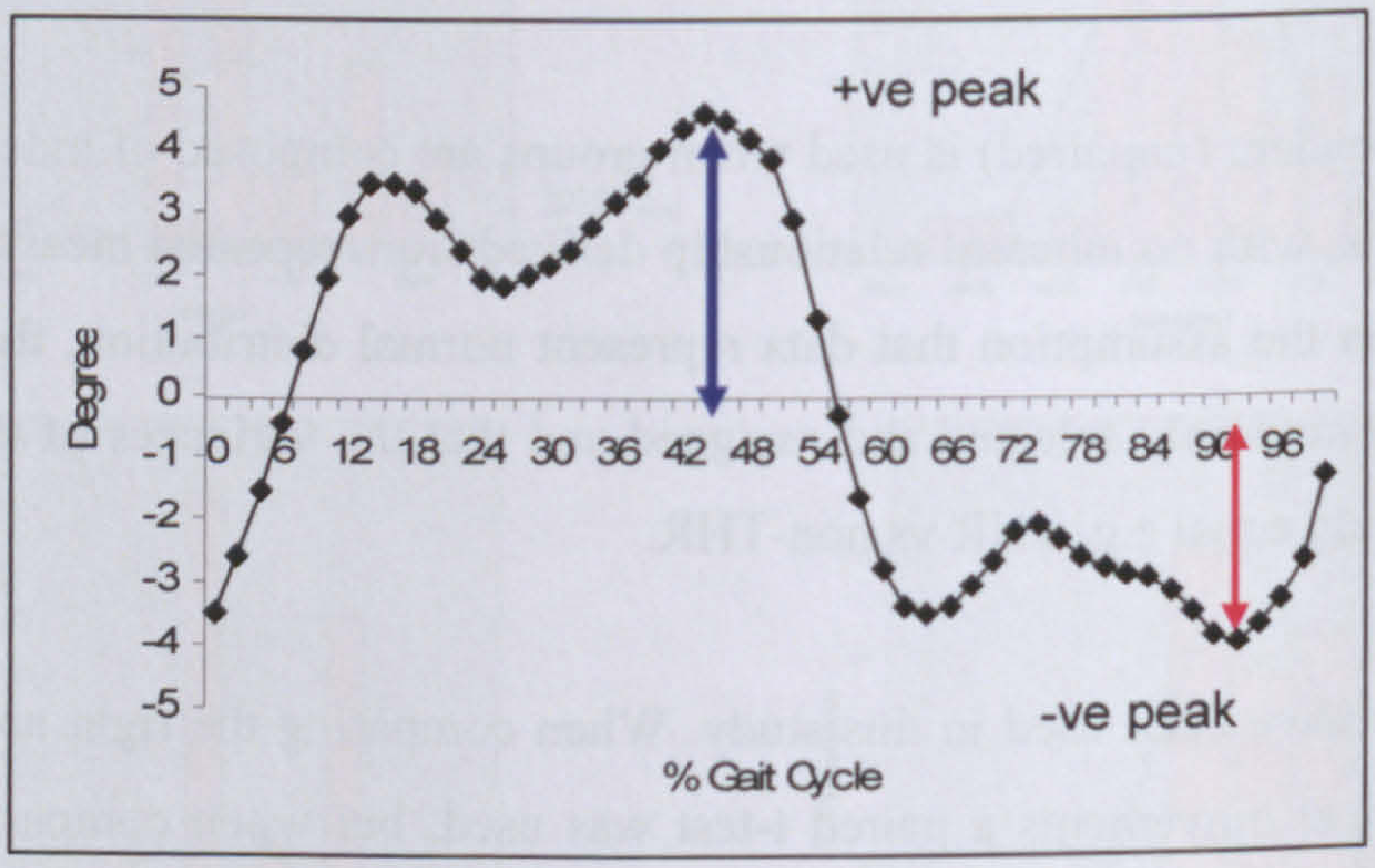


Figure 6.10 Calculation of peaks of movement through the gait cycle from maximum +ve peak value (Blue line) to maximum –ve peak value (Red line).

6.6.2 Biomechanical Data

A total of 52 participants undertook four functions with three trials per function, giving a total of 3012 trials for analysis. The mean range and standard deviation of each of the movement patterns were collated for each group (Hip replacement group – operated side (THR Op), Hip replacement group – non operated (THR Non Op) and control group (THN)).

Descriptive analysis (mean±SD) on the mean angle range and moment data at the gait events of initial contact and pre-swing (toe off) were also undertaken. Mean range was taken as the difference between the maximum magnitudes of the +ve and –ve peaks (Figure 6.9). Mean peak moments are also presented and these are defined as the largest moment in either the +ve or –ve direction (Figure 6.10).

Data for right and left sides of the THN group were collated as there was no significant difference between the sides for any of the biomechanical data collected. Full details and statistical analysis can be found for hip motion through the gait cycle in Appendix R, pelvic motion through the gait cycle in Appendix S, lumbar spine motion in appendix T and hip joint moments in appendix V.

Group movement patterns were collated and compared by the construction of single plane angle time graphs for each group for each of the hip, pelvis and lumbar spine movement segments and a single plane moment time graph for hip moments. Angle/ angle diagrams were then plotted for each of the movements with comparison of the group results through different colour representation. Statistical analysis of the movement patterns was not recommended for the biomechanical movement patterns, however observational analysis was undertaken.

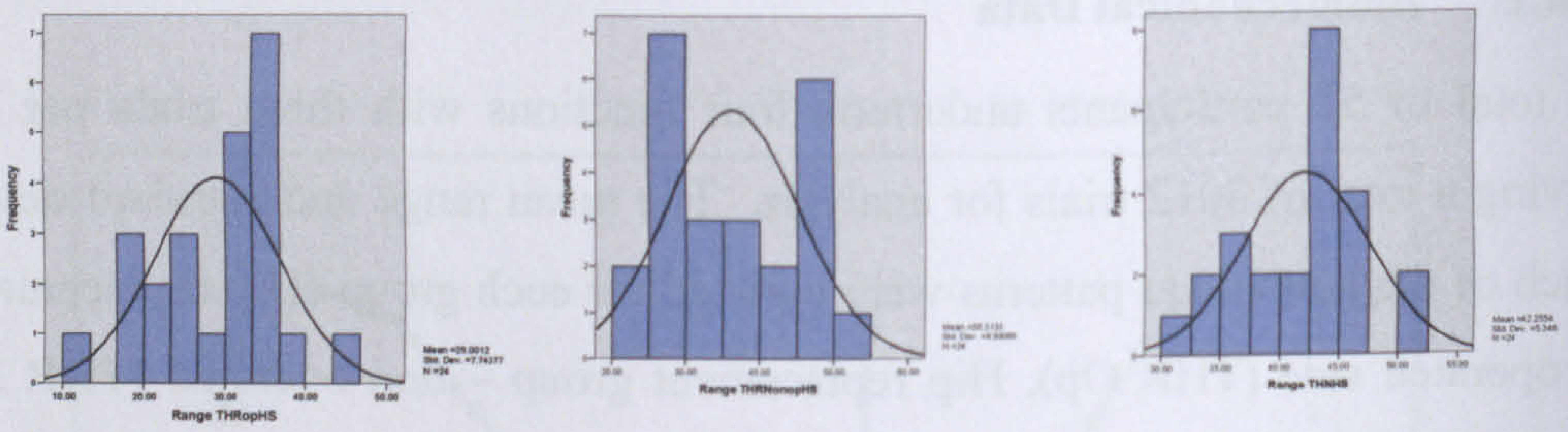


Figure 6.11 Sagittal Plane Hip Movements

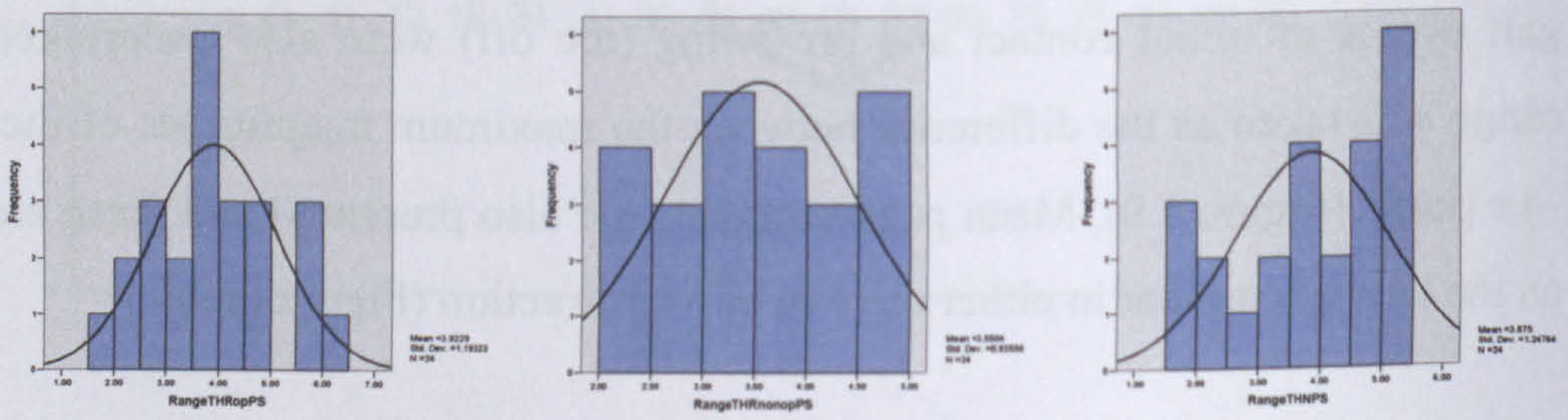


Figure 6.12 Sagittal Plane Pelvic Movements

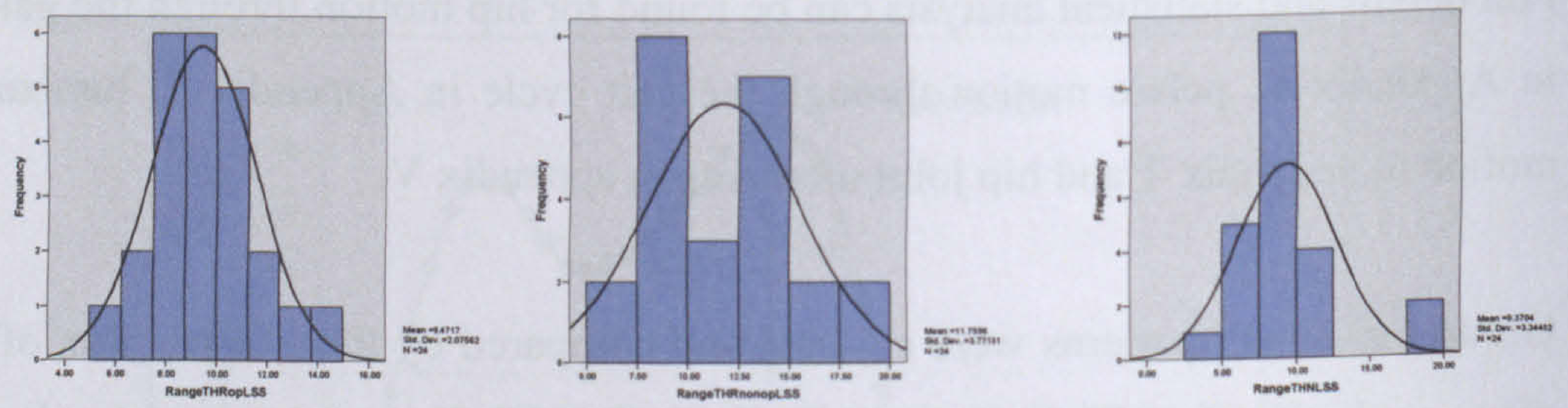


Figure 6.13 Sagittal Plane Lumbar Spine Movements

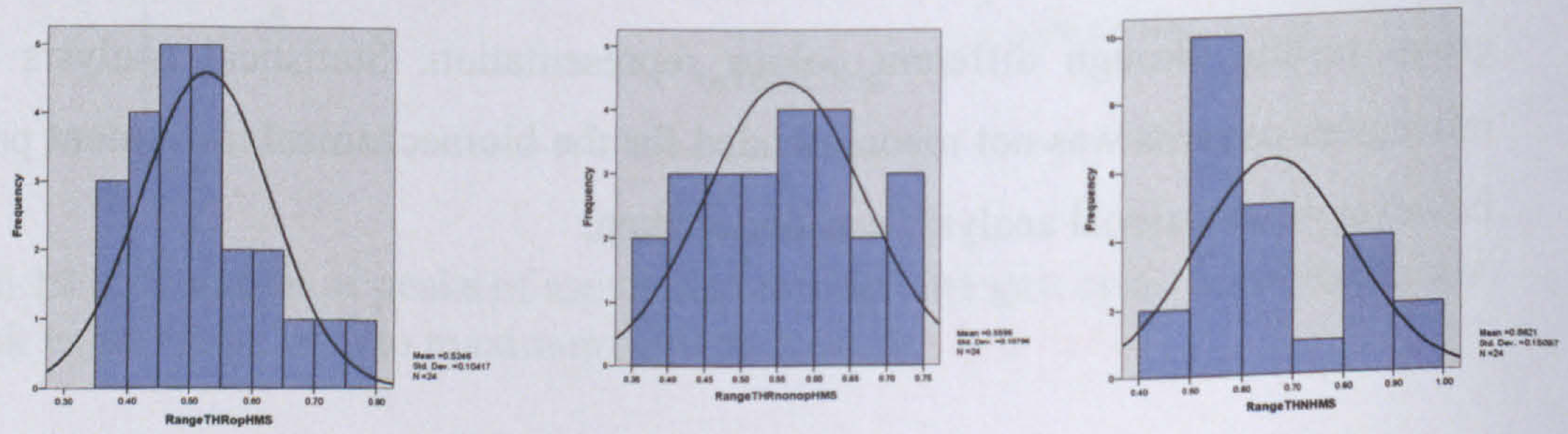


Figure 6.14 Sagittal Plane Hip Moments

Full details can be found in Appendix R,S,T,V

All mean movement data at heel strike and toe off, and peak moments were tested for normality using either the Shapiro Wilks test, if the samples were less than 50. Examples of normal distribution histograms for demographic and physiological data can be found in Figures 6.11 – 6.14, full details can be found in Appendix R, S, T, V.

One way ANOVA was used to assess differences in the mean data at key points in the pattern and ranges of dynamic movement between the three study groups, when the data demonstrated normality. Post hoc related and unrelated student t-tests were used if the results from the ANOVA were significant.

Table 7.1 Gender, Age, weight and height for the whole group and per group

	Gender (n) (M:F)	Age (yrs) (SD) Range	Weight (kg)(SD) Range	Height (m)(SD) Range
All (n=48)	14M: 36F (1:2.6)	73.96 (4.55) 63 - 84	65.38 (11.78) 45 – 93	1.62 (0.09) 1.50 – 1.85
THR group (n=24)	5M: 19F (1:3.8)	74.81 (4.89) 66 - 82	64.62 (12.29)* 45 - 85	1.61 (0.08)** 1.50 – 1.80
(THN group (n=24)	8M: 16 F (1:2)	73.04 (4.05) 63-83	66.21 (11.42) 50 – 93	1.64 (0.09) 1.53 – 1.85
Key: * p = 0.018, ** p = 0.009				

7.0 CLINICAL RESULTS AND DISCUSSION

The results are presented in two chapters; Chapter 7 outlines the details of the participants and the findings of the measurement of passive physiological movement and discusses these findings. Chapter 8 addresses the findings and analysis of the biomechanical data.

7.1 PARTICIPANTS

Two groups (those with Total Hip Replacements (THR) and those without (THN)) of 24 participants were recruited. The groups were matched by age, gender and all participants were physically active. The THR group all had a primary total hip replacement undertaken by the same orthopaedic surgeon in either a NHS or private hospital, using the same type of hip prosthesis and surgical procedure. Data was collected on 26 people following THR but the kinetic data from one participant was incomplete and therefore their data was excluded from the calculations. Another participant was excluded from the study, as she was less mobile than her norm due to an injury which occurred after agreeing to take part in the study. The data on the remaining 48 study participants (24 in each group) will be presented.

7.1.1 Demographic data

There was no significant difference ($p>0.05$) between the age, weight or height of the participants in the THR and THN groups when tested by independent sample t-test (Table 7.1). The raw data and full statistical analysis can be found in Appendix M. The ratio of males to females was 1:2.6 for the whole group, the ratio fell slightly in the THN group to 1:2, and was greatest for the THR group. The groups were matched for gender with no significant difference found using Chi square analysis ($\chi^2 = 1.6879$, $p > 0.05$). Calculations can be found in Appendix M.

Comparison of the groups by gender for age, height and weight was undertaken using two-way analysis of variance. There was no significant difference for age

Table 7.2 Gender, age, weight & height for Total hip replacement group (n= 24)

THR group	Numbers	Age (years) (SD)	Height (m) (SD)*	Weight (kg) (SD)*
Males	5	77.20 (4.15)	1.73 (0.57)	78.20 (6.46)
Range		71 - 81	1.66 - 1.8	70 - 85
Females	19	73.63 (4.65)	1.57 (0.044)	59.37 (9.48)
Range		66 - 82	1.49 – 1.66	45 - 76
Key: * Significant at p=0.001				

Table 7.3 Gender, age, weight & height for the non-total hip replacement group (THN) (n=24)

THN group	Numbers	Age (years) (SD)	Height (m) (SD)*	Weight (kg) (SD)**
Males	8	73.13 (2.95)	1.73 (0.09)	74.38 (14.23)
Range		70 - 78	1.56 – 1.85	52 - 93
Females	16	73.00 (4.59)	1.59 (0.04)	62.13 (7.21)
Range		63 - 83	1.53 – 1.68	50 - 76
Key: * Significant at p=0.003, ** Significant at p=0.048				

between the males and the females in the THR and THN group but there were significant differences by height (p=0.009) and weight (p=0.018) (Table 7.2) (Appendix M for statistical analysis). Post hoc analysis (independent t-tests) to distinguish where the differences existed identified that the male participants in each group, were significantly taller (THR p=0.001, THN p=0.003) and heavier (THR p=0.001, THN p=0.048) than their female counterparts (Table 7.2 & 7.3).

7.1.2 Operation details and answers to function questions

The results of the general questions outlined in Appendix J are summarised below. Full data on this subject can be found in Appendix N.

THR group only

- Operated side: The majority of THR surgery was to the right leg (n=15, 62.5%) with only nine people having surgery on the left.
- Time since operation: Average time since operation was 27.67±8.81 months with a range of 20-49 months. Ten people were measured earlier than the expected time of 24 months following surgery but no one had surgery less than 20 months before taking part in the study.

Both groups

- Walking Aid: Eight people in the THR group used a walking stick to assist outdoor walking but not for indoor function. All eight used the stick in the opposite hand to the operated side, for reassurance rather than to improve weight bearing. No one in the THN group used any type of walking aid.

- Hip Pain: Four people out of 24 (16.6%) in the THR group had some hip pain but this was minimal with a modal Visual Analogue Scale (VAS) score of one, range 1-2. Of the four people with hip pain, three complained of pain on the operated side and one on the non-operated side. No one in the THN group complained of hip pain.

- Lumbar Spine Pain: 15 people out of 24 (62.5%), in the THR group complained of some degree of lumbar spine pain, which interfered with their daily activity. The modal VAS score for this pain was two, with a range of 1-3. One person in the THN group (n=24, (4.2%)) complained of pain in the lumbar region (VAS =2) but this was intermittent and was not present during testing.

Of note the modal score for back pain was greater than that for hip pain but both were at a low level on the visual analogue scale.

7.1.3 Functional Ability

All participants in both the THR and THN group could both ascend and descend stairs with the use of a handrail without difficulty and did not complain of being unable to undertake everyday functional activities.

7.1.4 Previous surgery and medical problems

Numbers of previous surgical procedures were recorded and the findings can be found in (Appendix N). There was no obvious similarity for the type of previous surgery identified by the participants in each group. In the THR group, four people had had a total knee replacement (TKR) on the opposite side to their THR; all had full return of function. All TKR surgery had occurred prior to the person's total hip replacement. Four people in both groups had had a hysterectomy and four people in the THR group had previous cataract removal. All surgeries had occurred at least one year prior to their total hip replacements.

There are a number of differences between the groups concerning medical problems. Appendix N, indicates the type and frequency of medical problems in the groups. The result of interest was that many more participants in the THN group had no medical problems when compared to the THR group particularly that 15 in the THR group had some form of low back pain, compared to one in the THN group. More people had osteoarthrosis (OA) of the hands and feet in the THR group (6 vs 2), but the reverse was so for OA knee (3 vs 2).

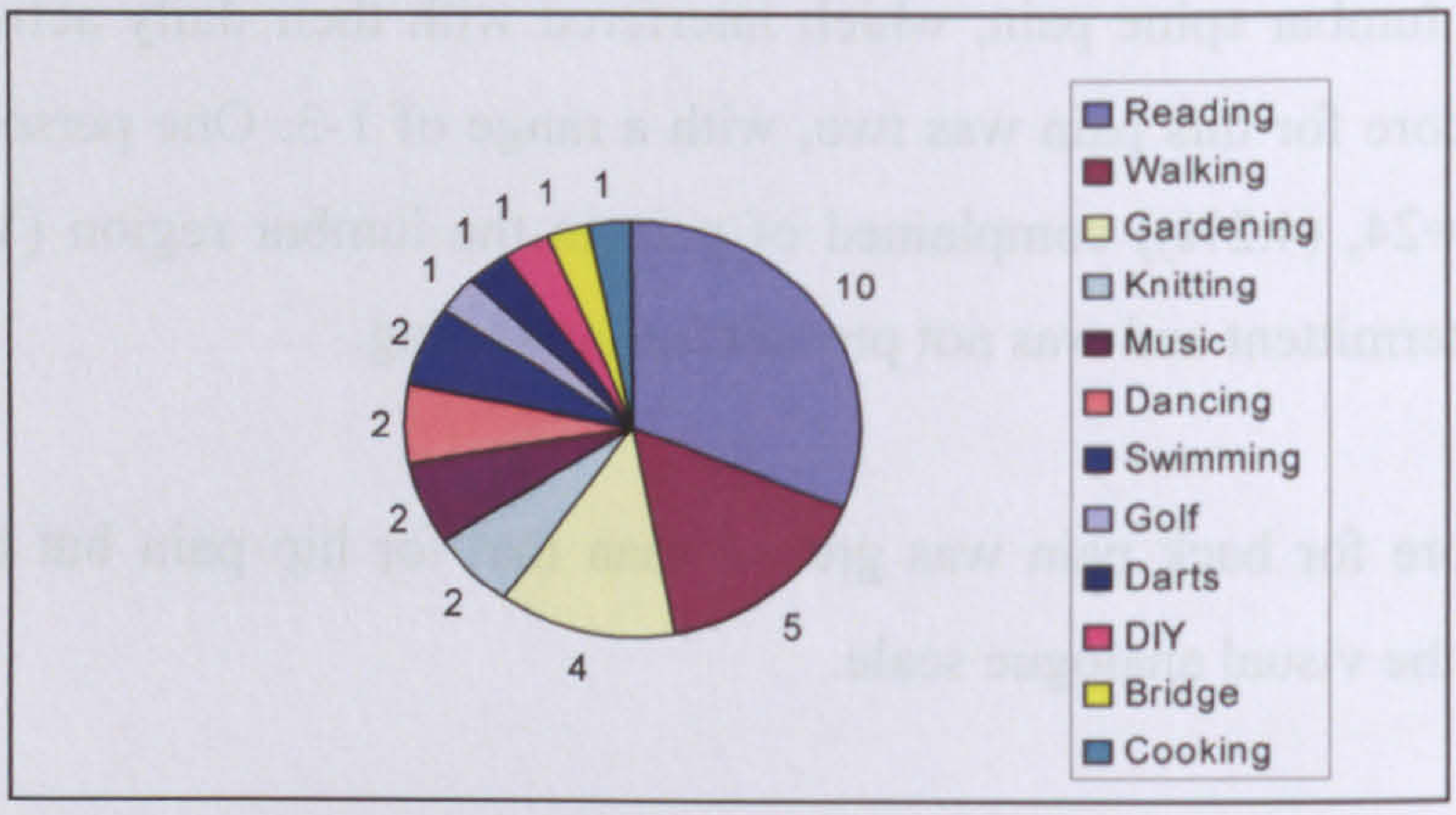


Figure 7.1 Frequency distribution of hobbies: THR group (n = 24)

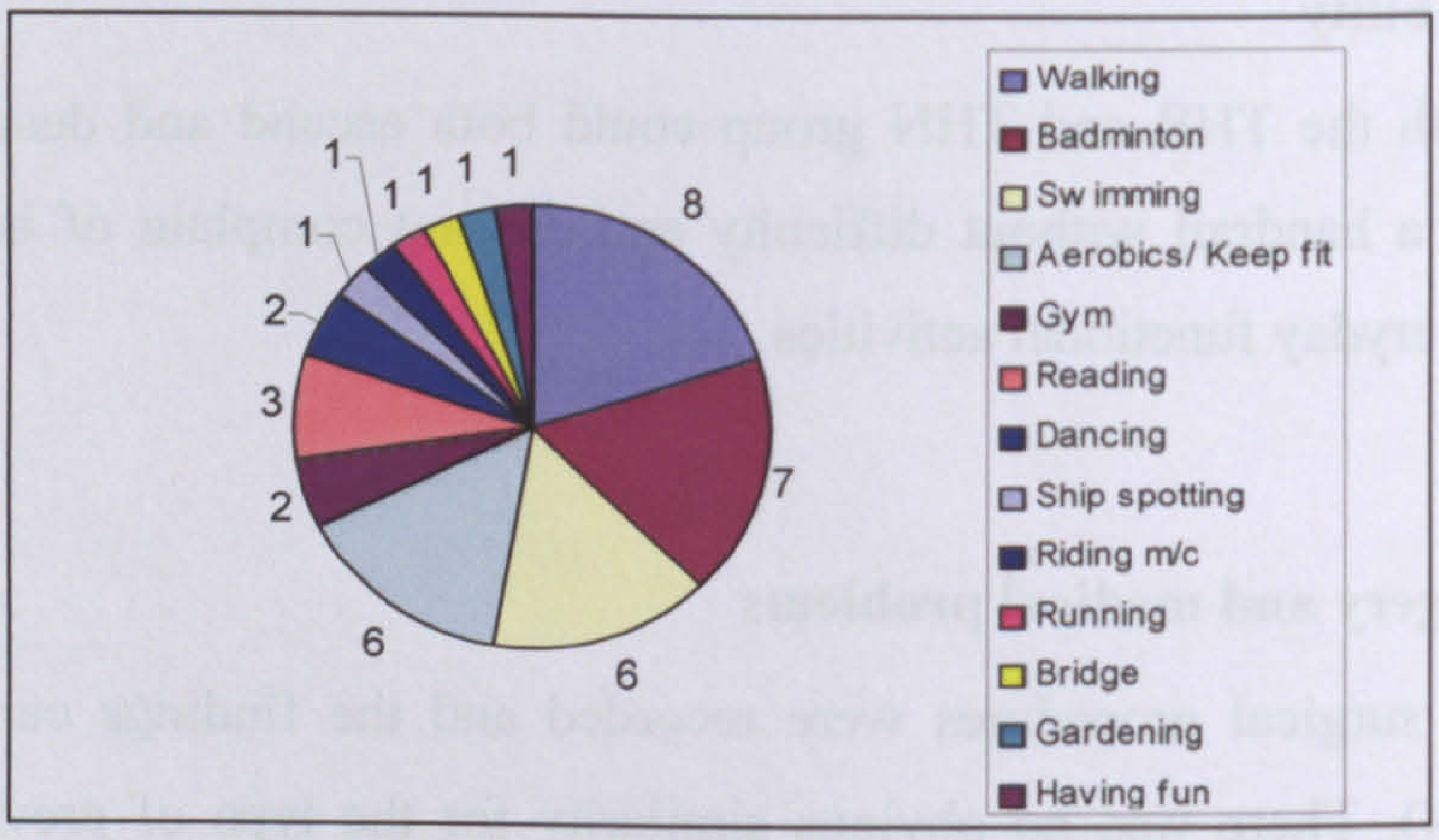


Figure 7.2 Frequency distribution of hobbies: THN group (n = 24)

Table 7.4 Active and Passive leisure activities

Passive	THR	THN	Active	THR	THN
Reading	10	3	Walking	5	8
Ship spotting	0	1	Badminton	0	7
Riding m/c	0	1	Swimming	2	6
Bridge	1	1	Aerobics/Keep fit	0	6
Cooking	1	0	Gardening	4	1
Darts	1	0	Gym	0	2
Knitting	2	0	Dancing	2	2
Music	2	0	Running	0	1
Having fun	0	1	DIY	1	0
			Golf	1	0
Total events	17	7		15	33

7.1.5 Hobbies

The THR group participants identified a number of hobbies, with all participating in some form of active leisure pursuit. With a total of 32 responses, eight people had more than one hobby, the commonest hobby was reading followed by walking and gardening (Figure 7.1).

In contrast the THN group made 40 responses regarding hobbies and all participated in more than one leisure pursuit. Walking, badminton, aerobics/ keep fit and swimming gained the highest responses (Figure 7.2) with all THN participants having at least one active pastime.

From the list of hobbies and the number of people undertaking these, it appears that on the whole the THR group participants have more passive leisure pastimes compared to the THN group. If the leisure activities are grouped into active and passive as listed below (Table 7.4) and the number of events collated, the discrepancy is clearly seen. The division between active and passive leisure pursuits was purely arbitrary based on broad headings. Using Chi square statistical analysis there is a significant difference ($\chi^2 = 13.55$, $p<0.0001$) (Full statistical Analysis in Appendix N) between the two groups, with the THN taking part in more active leisure activities.

There was no attempt to obtain more information about the level or duration of activity or compare the leisure pursuits to pre and post THR surgery. Neither was it ascertained if more active leisure pursuits were inhibited because of the hip surgery or any other medical/ surgical problems.

7.1.6 Leg Lengths

Leg lengths were measured for both true and apparent lengths and the raw data can be found in Appendix N. Comparisons were made between the right and left leg lengths within each group and between the groups for both true and apparent measures (Table 7.5, p150A) and between operated and the non-operated leg for the

Table 7.5 Mean (SD) and differences true and apparent leg lengths (m)(n= 24 each group)

	Mean Length (SD) (m)		R-L	Range of
	Right leg	Left leg	Mean difference (SD) (cm)	R-L difference (cm)
True THR	0.84 (0.05)	0.84 (0.05)	-0.14 (0.80)	(-2) to 2
True THN	0.86 (0.05)	0.86 (0.05)	0.08 (0.30)	(-0.2) to 1
App THR	1.095 (0.05)	1.098 (0.05)	-0.29 (1.13)	(-3.5) to 1
App THN	1.08 (0.06)	1.08 (0.06)	0.04 (0.24)	(-0.4) to 0.6

Key: THR – total hip replacement
THN – no total hip replacement
True – leg length from ASIS to medial malleolus
App – Apparent leg length from Xyphoid sternum to medial malleolus
R-L The difference between leg length: right minus left

Table 7.6 Difference in leg lengths (m) between the operated and non-op leg (n=24)

THR group Leg Length	Mean Length (SD) (m)		Comparison between legs, p value	Mean differences between legs (SD) (cm)	Range of differences (cm)
	Operated leg	Non-operated leg			
True	0.84 (0.042)	0.84 (0.047)	0.66	-0.07(0.80)	(-2) to 1
Apparent	1.098(0.05)	1.095(0.05)	0.33	-0.23(1.15)	(-3.5) to 2.5

Key: THR – total hip replacement,
True – leg length from ASIS to medial malleolus
App – Apparent leg length from Xyphoid sternum to medial malleolus

Table 7.7 Frequency and mean of leg length differences (cm) by category and measurement (THR Group)

Categories	THR true leg length		THR apparent leg length	
	Frequency	Mean (SD) (cm)	Frequency	Mean (SD) (cm)
Operated leg longer	5	1.39 (0.78)	9	1.50 (1.27)
Equal Leg lengths	8		9	
Operated leg shorter	11	0.47 (0.21)	6	0.98 (0.94)

THR group (Table 7.6). Mean differences in leg lengths are presented in Table 7.5. The statistical analysis is presented in Appendix N.

7.1.6.1 Differences between operated and non-operated leg length

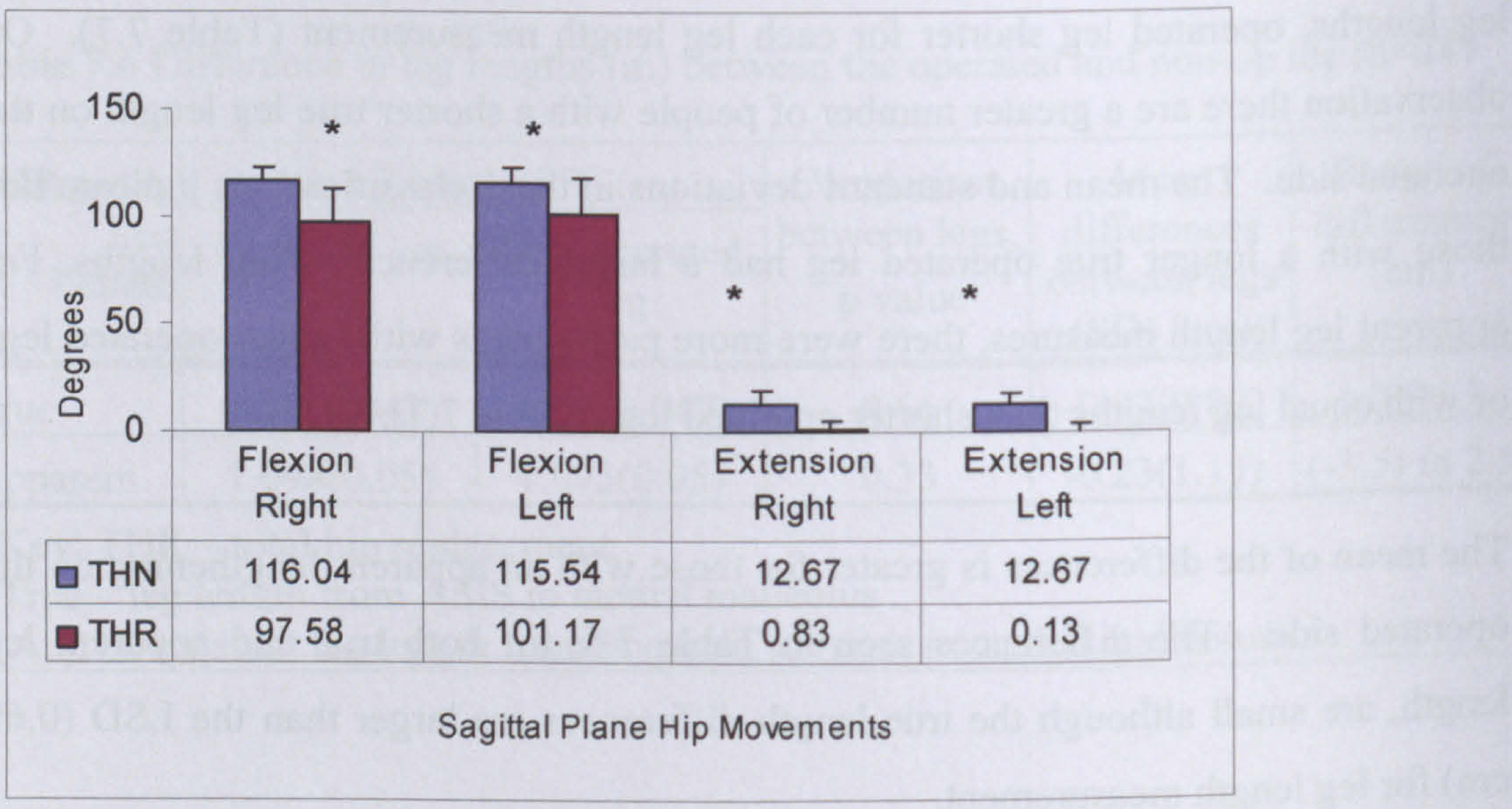
Comparison of leg lengths between the operated and non-operated leg in the THR group showed no significant difference for both true and apparent readings using a paired t-test (Table 7.6). Overall the operated leg was marginally longer than the non-operated one, but the mean of the difference (0.07 cm) falls well below the measurement error (LSD). The results for apparent leg length differences are skewed because one person had a difference of 3.5 cm, with the operated side being longer (See raw data, Appendix N).

The data was then compared visually in three categories: operated leg longer, equal leg lengths, operated leg shorter for each leg length measurement (Table 7.7). On observation there are a greater number of people with a shorter true leg length on the operated side. The mean and standard deviations in these classifications indicate that those with a longer true operated leg had a larger difference in leg lengths. For apparent leg length measures, there were more participants with longer operated legs or with equal leg lengths than shorter operated legs (Table 7.7).

The mean of the differences is greater for those with an apparent lengthening on the operated side. The differences seen in Table 7.6, for both true and apparent leg length, are small although the true length differences are larger than the LSD (0.69 cm) for leg length measurement.

7.1.6.2 Differences between right and left leg lengths

There was no significant difference between the right and left leg lengths or participant groups as calculated by two factor repeated ANOVA; true leg length (overall $p=0.243$, side $p=0.729$, group $p=0.386$), apparent leg length (overall $p=1.66$, side $p=0.306$, group $p=0.261$). The overall mean and standard deviations for the right and left side are given in Table 7.5.



	Flexion Right	Flexion Left	Extension Right	Extension Left
🟦 THN	116.04	115.54	12.67	12.67
🟥 THR	97.58	101.17	0.83	0.13

Figure 7.3 Comparison of mean and standard deviations of hip flexion and extension (°) by side and group (n=24 per group), * p<0.0001

The mean of the differences in leg lengths was undertaken to see if there was a directional trend (Table 7.5, p149A). Any differences greater than the LSD for leg length measurements (LSD = 0.69cm, see section 5.4.5, p128) were noted. No-one in the THN group had either a true or apparent leg length difference greater than the LSD for this measurement (See Appendix N).

Three people in the THR group had larger true leg length differences of 1.75, 2.0 and 2.0 cm with two having a longer left leg and one, right, all were longer on their operated side (See Appendix N for raw data). Four people had large apparent right to left differences. The apparent differences were 1.5, 2.0, 2.5 and 3.5 cm with the left leg being longer in all cases (See Appendix N) for raw data).

The range of differences for the THR group was greater than the THN with larger standard deviations particularly for apparent leg length.

7.2 PASSIVE PHYSIOLOGICAL MOVEMENT

Passive physiological measurements of the hip and lumbar spine were taken for all participants in each of the two groups. The results are presented firstly for the hip by plane of movement for the right and left sides, then for the THR group by operated and non-operated side, then for the lumbar spine and finally the knee. The raw data and the statistical analyses are in Appendix O & P.

7.2.1 Hip Movement: Clinical measures comparisons for left and right by group

7.2.1.1 Sagittal plane movement

The THR group had less motion than the THN group for both flexion and extension. Significant differences ($p<0.0001$) in sagittal plane hip movement were found on repeated measures analysis of variance by group but not by side (Figure 7.3), for both flexion and extension movements (See Appendix O2(a)).

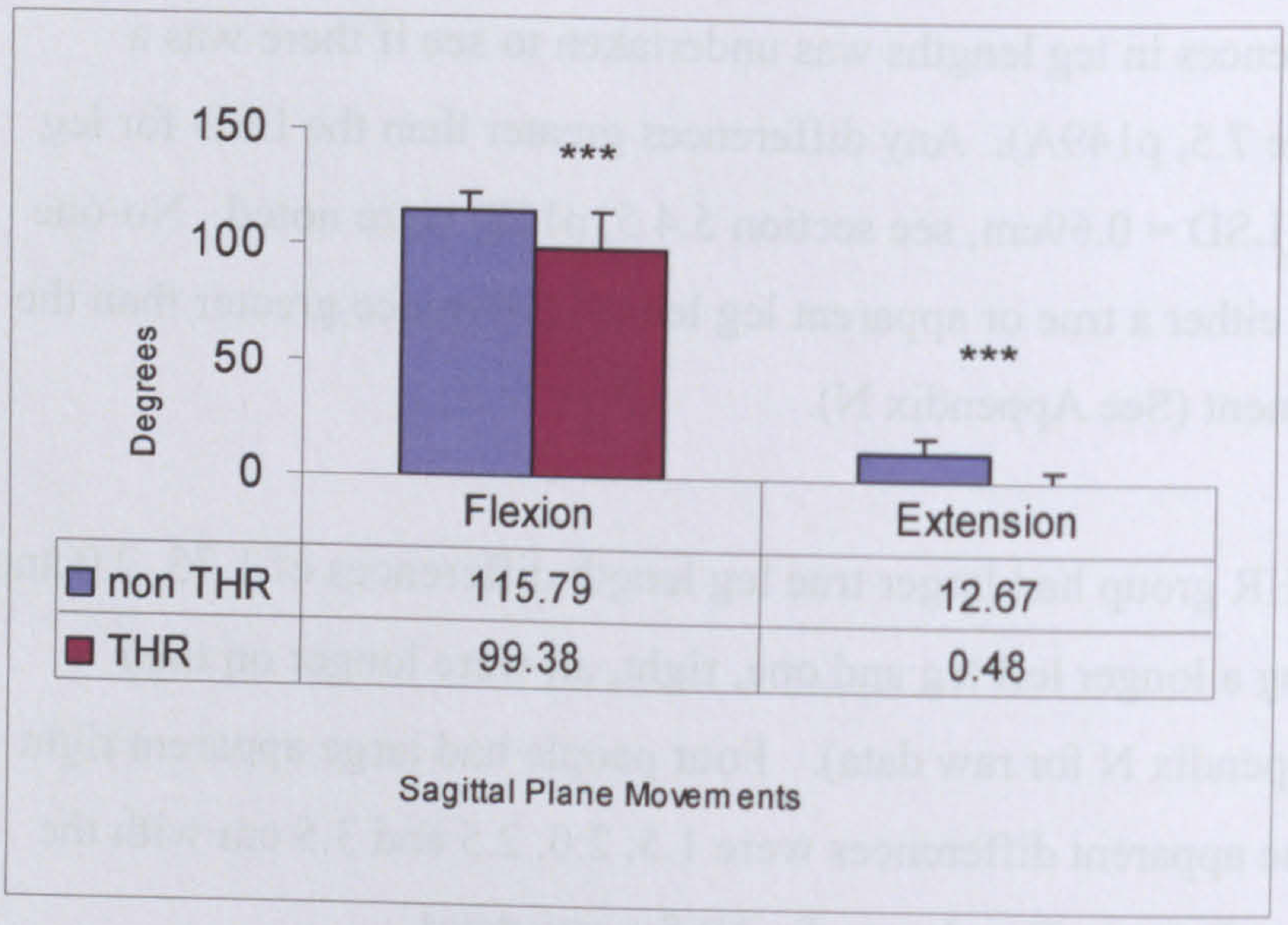


Figure 7.4
Comparison of hip flexion and extension movement (°) between the groups (n = 48 per group), *** p<0.00001

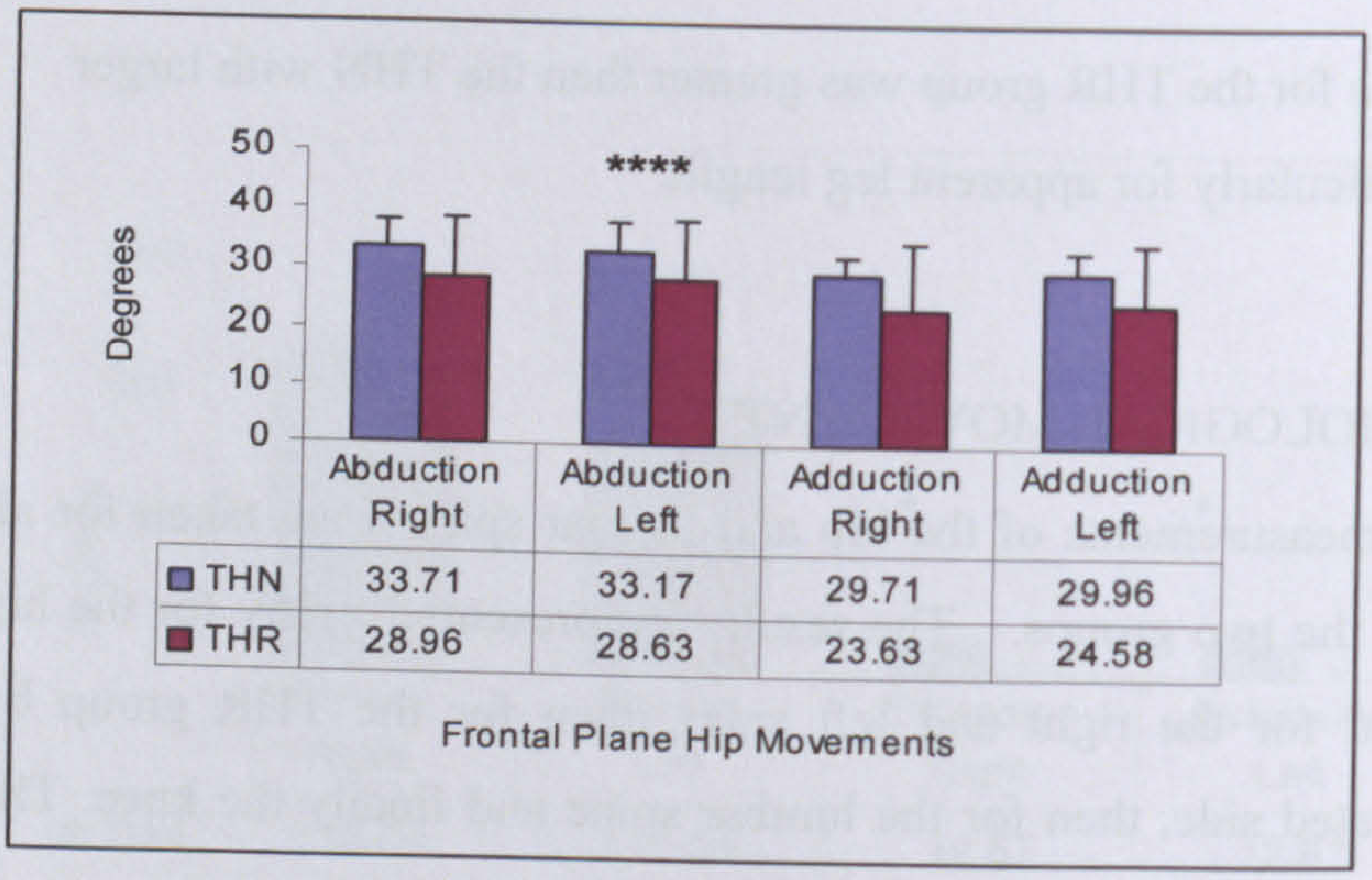


Figure 7.5
Comparison of mean and standard deviations of hip abduction and adduction (°) by side and group (n=24 per group)
**** p=0.0002

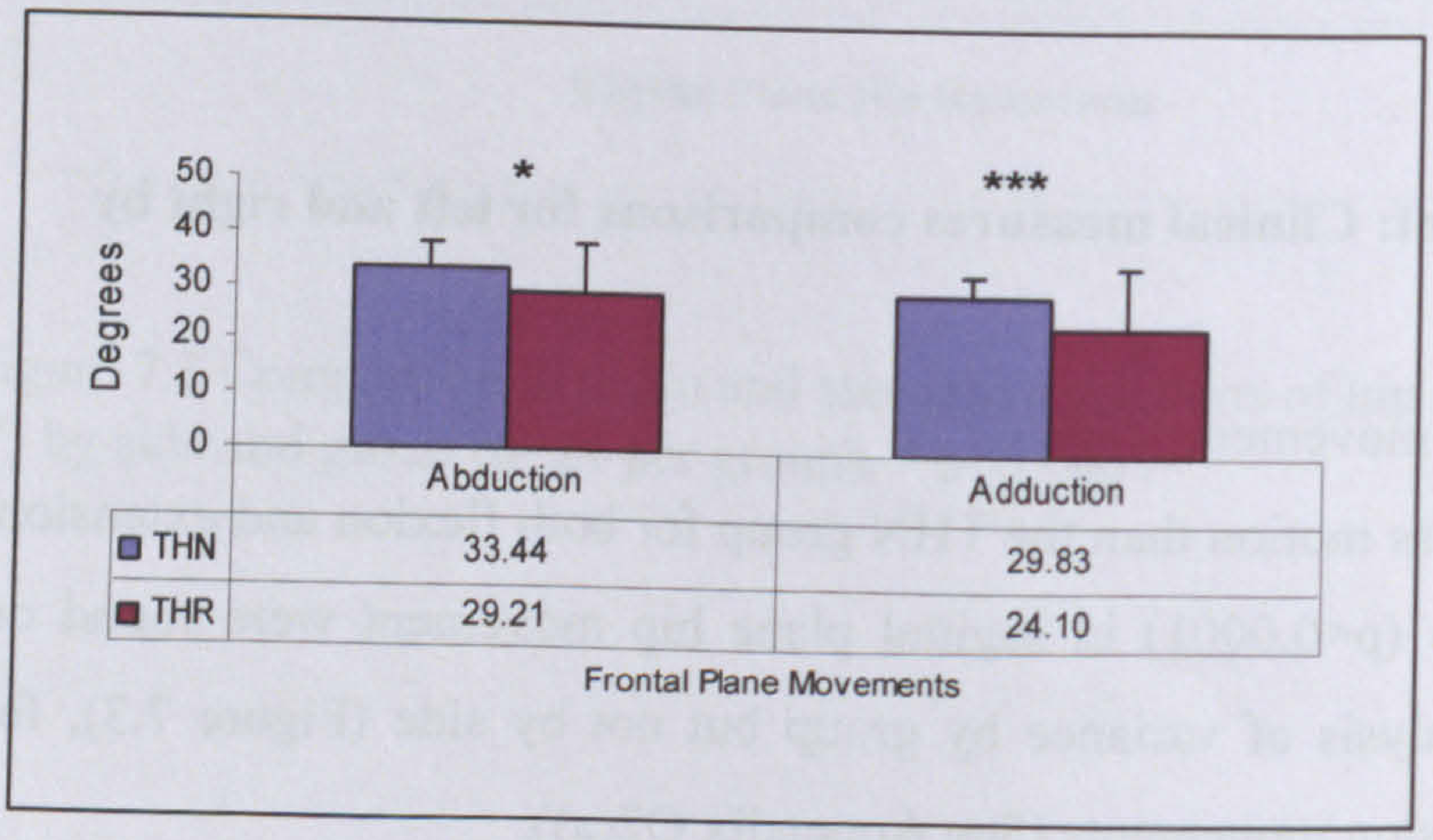


Figure 7.6
Comparison of Abduction and Adduction movement (°) between the groups (n = 48 per group),
*p=0.04,
***p< 0.0001

As there was no significant difference between right and left sides (flexion p=0.217, extension p=0.477) for either group, post hoc comparison of group data for flexion and extension was undertaken using both right and left data together. Figure 7.4 shows the mean and standard deviations for each of the groups, using an independent sample t-test, a significant difference was found between the groups (p<0.0001) for both flexion and extension.

7.2.1.2 Frontal plane movement

Measurements in the frontal plane again demonstrated that the THR group had less motion for all measures (Figure 7.5). The standard deviations for the THR groups were much greater than the THN group indicating greater variability in the frontal plane (Figure 7.5). Analysis by repeated measures ANOVA for abduction by side and group indicated no significance value (p=0.084), but for adduction there was a strong significant difference (p= 0.0002).

Post hoc statistical analysis by paired t-test indicated that there was no significant difference by side, the data for both left and side right side was therefore combined in further analysis. When analysed by independent sample t-test, there was a significant difference between the THR and THN groups, in the range of abduction (p=0.04), but for adduction the difference was highly significant (p<0.0001) (Figure 7.6, Statistical Analysis, see Appendix O2 (b)). Movement was greater in the THN group for both movements, with adduction having the greatest variance, due to the large standard deviations.

7.2.1.3 Horizontal plane movement

Range of movement in the horizontal plane was collected with the hip in two positions; in full extension and with the hip in 70° of flexion. The raw data can be found in Appendix O 1(c), and the mean and standard deviations in Table 7.8 (p153).

Visual comparison of the data by hip position (Table 7.8) indicates that for both lateral and medial rotation in both positions the THR groups have less motion than the THN group.

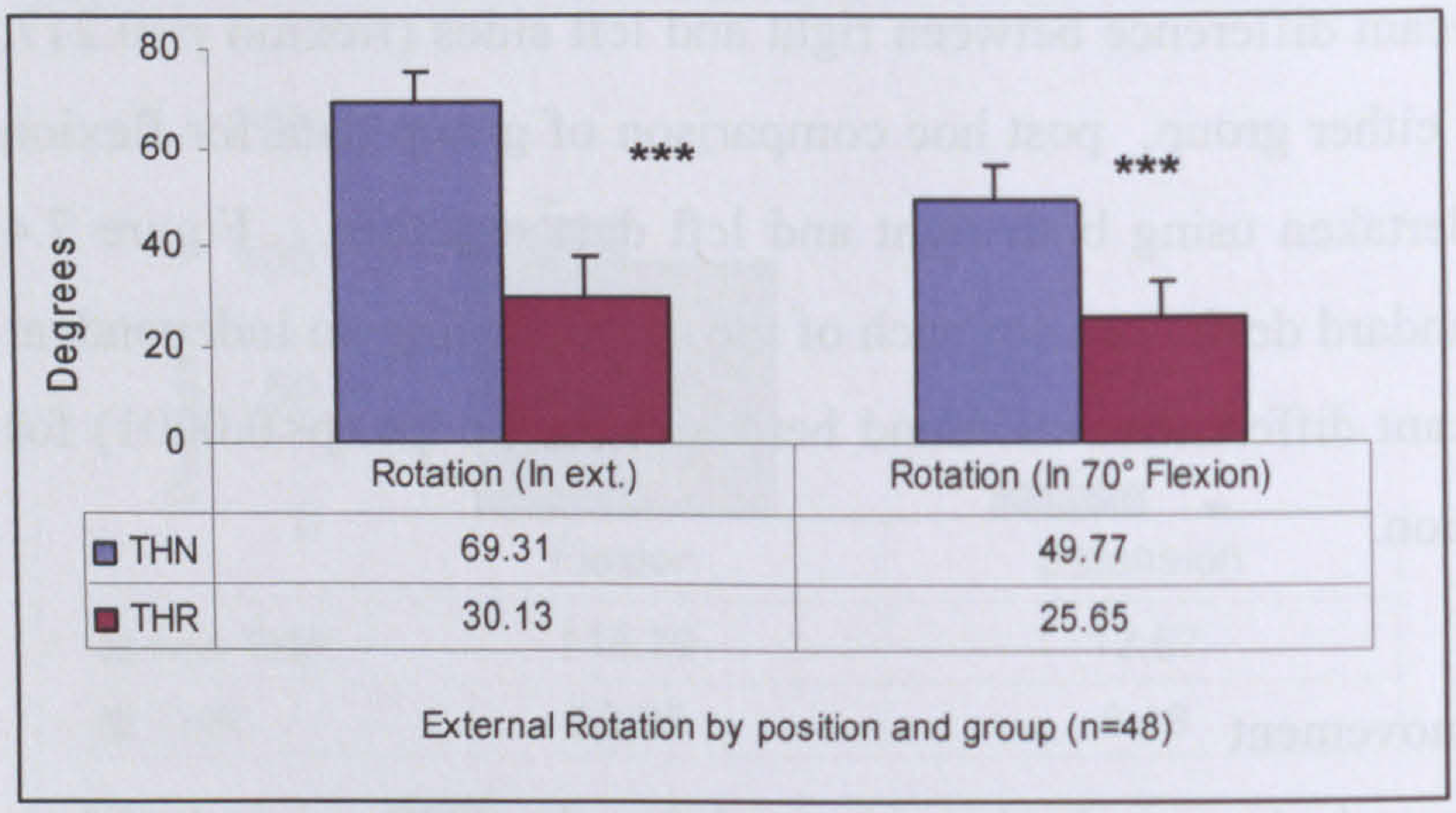


Figure 7.7 Comparison of mean lateral hip rotation data (°) measured in both positions by group THN versus THR (n=24) *** =significant at p<0.0001

Table 7.9 Statistical comparison (Repeated ANOVA) of right to left hip rotation in 2 positions

Significance values (paired t-test)	Left vs Right comparison	
Hip in full extension	THR	THN
Medial Rotation	0.003*	0.003*
Hip in 70° Flexion		
Medial Rotation	0.003*	0.05
Key: * Significant p<0.05, **all data in degrees**		

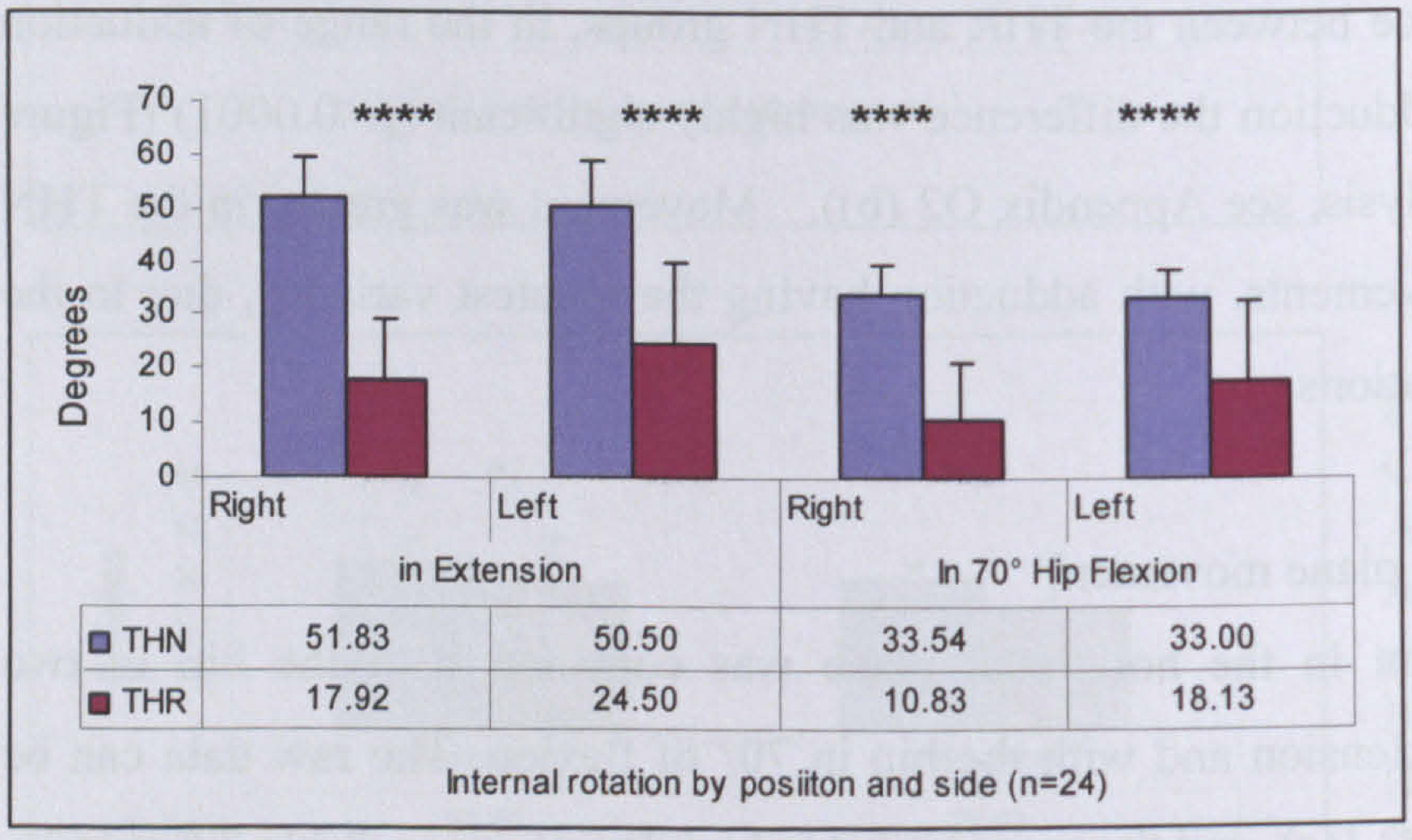


Figure 7.8 Comparison of mean medial hip rotation data (°) (unpaired ttests) measured both positions by side and group (n=24), *** =significant at p<0.0001

Table 7.8 Mean and Standard deviations for hip rotation data for both groups by side

	RIGHT				LEFT			
	In extension		In 70° Hip Flexion		In extension		In 70° Hip Flexion	
Rotation Mean (SD)	Lat.	Med.	Lat.	Med.	Lat.	Med.	Lat.	Med.
THN	69.63 (6.91)	51.83 (7.68)	49.54 (7.69)	33.54 (5.41)	69.00 (5.62)	50.50 (8.13)	50.00 (7.72)	33.00 (5.13)
THR	30.33 (11.51)	17.92 (11.37)	24.17 (12.04)	10.83 (10.18)	29.92 (11.85)	24.50 (15.32)	27.13 (15.03)	18.13 (14.43)
Key: Lat. – Lateral rotation, Med. – Medial rotation, all data in degrees								

Repeated measures ANOVA showed that for lateral rotation in both positions (hip extension and 70° hip flexion) there were significant differences by group ($p<0.0001$) but not by side (extension $p=0.14$, flexion $p=0.305$), post hoc independent t-tests were undertaken for comparison of group results combining the data for each side. These showed a significant difference ($p<0.0001$) for both flexion and extension positions between the THR and THN groups. The THN group had more lateral rotation than the THR group. (Figure 7.7) (See Appendix O).

Analysis of medial rotation by repeated measures ANOVA indicated significant differences for both group ($p<0.0001$) and side ($p<0.001$) in either hip position except THN in 70 hip flexion which was only just not significant (Table 7.9). Post hoc analysis by independent t-test confirmed the difference ($p<0.0001$) between groups for right and left medial hip rotation in each of the groups for each hip position (Figure 7.8) (See Appendix O 2(a)). Bonferroni correction was applied as the data was used for two separate tests, therefore the p value needs to be <0.025 for there to be a significant difference.

All ranges of lateral rotation were greater than those for medial rotation and the standard deviations for the THR group were larger than for the THN group. (See Appendix O for details).

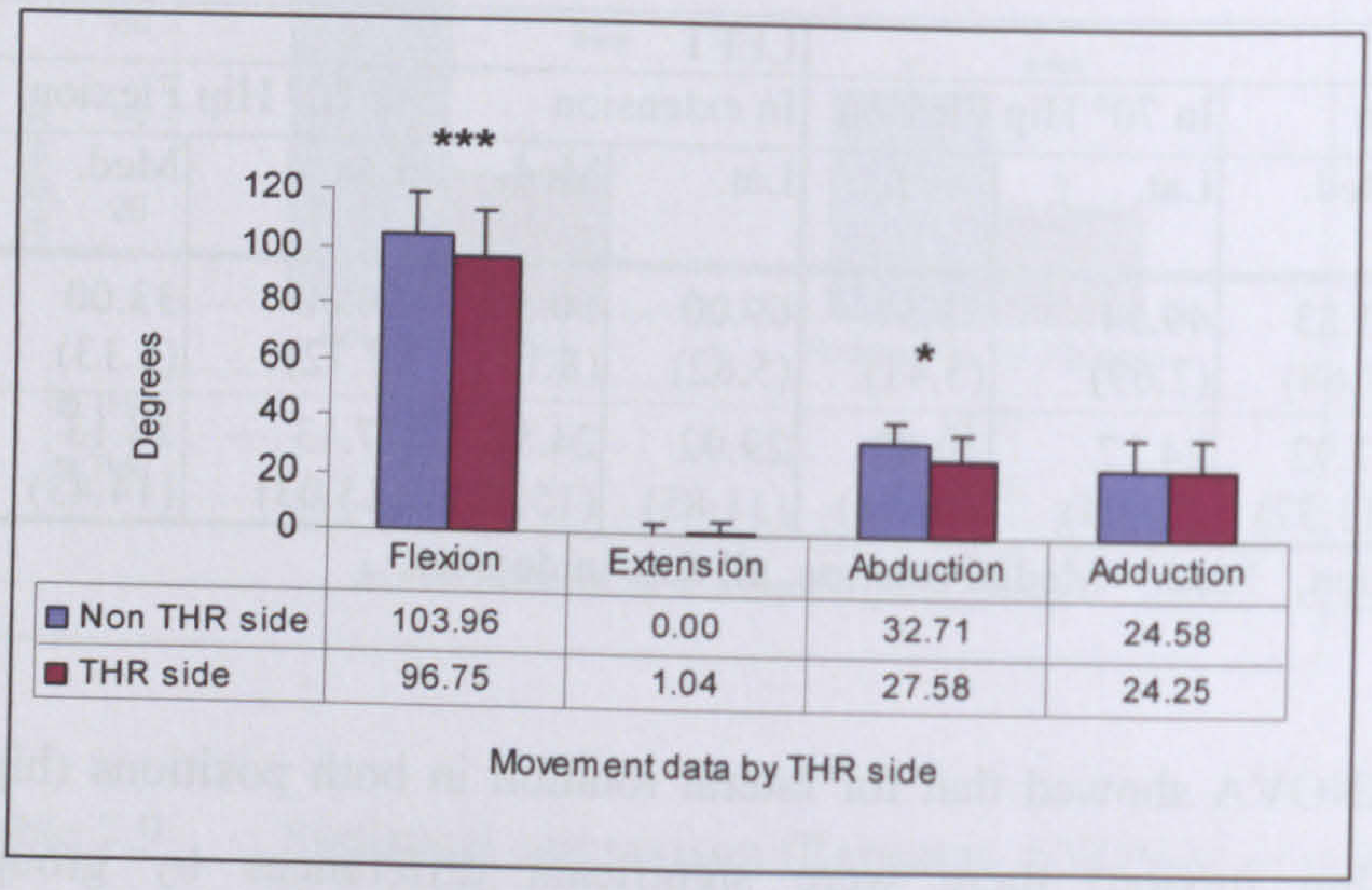


Figure 7.9 Comparison of sagittal and frontal plane hip movement for THR group by operation side, significant difference * p=0.04, ***p<0.001

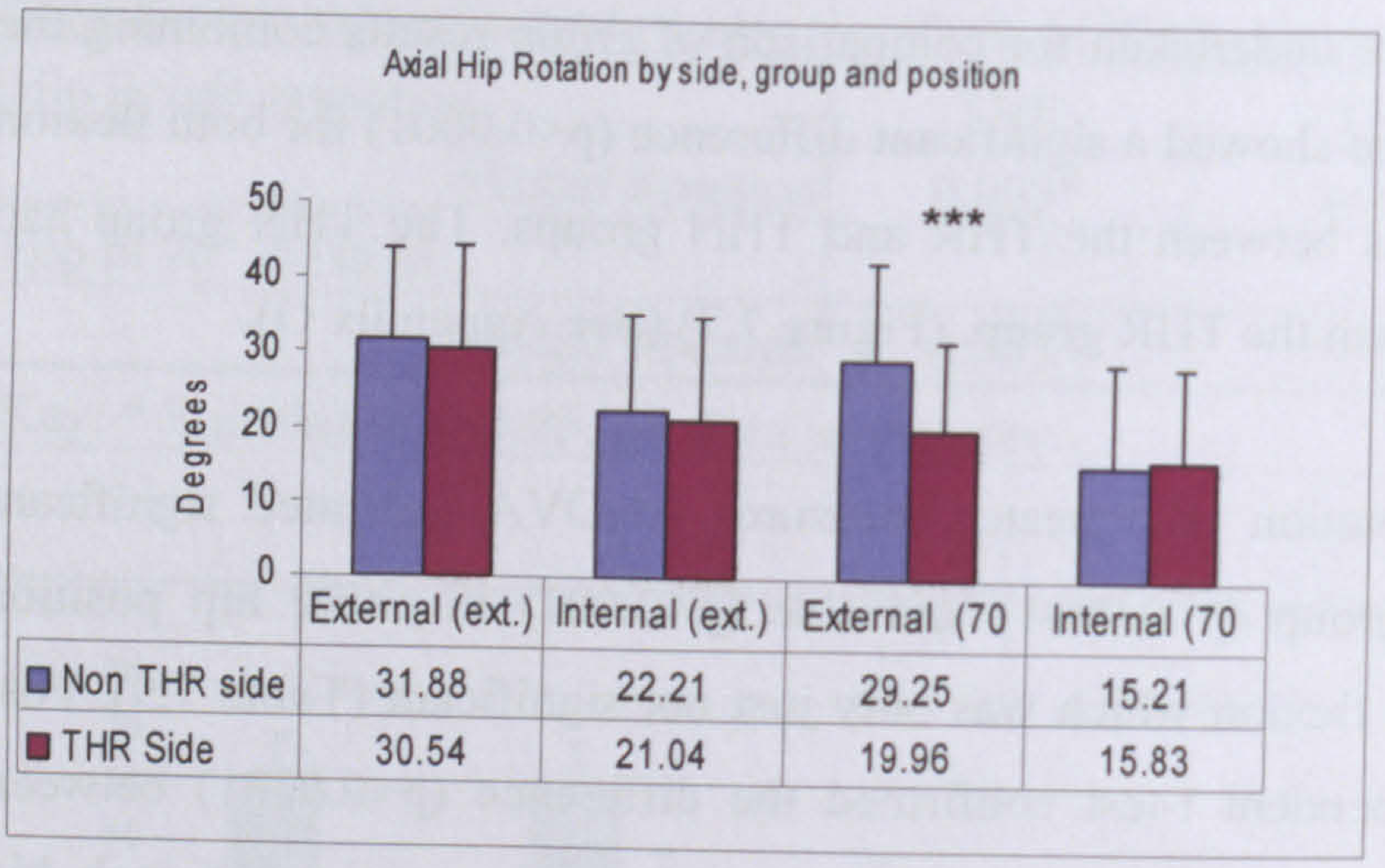


Figure 7.10 Comparison of hip axial rotation for THR group by operation side and position: ext = extension, (70) = 70° flexion, significant difference, ***p<0.001

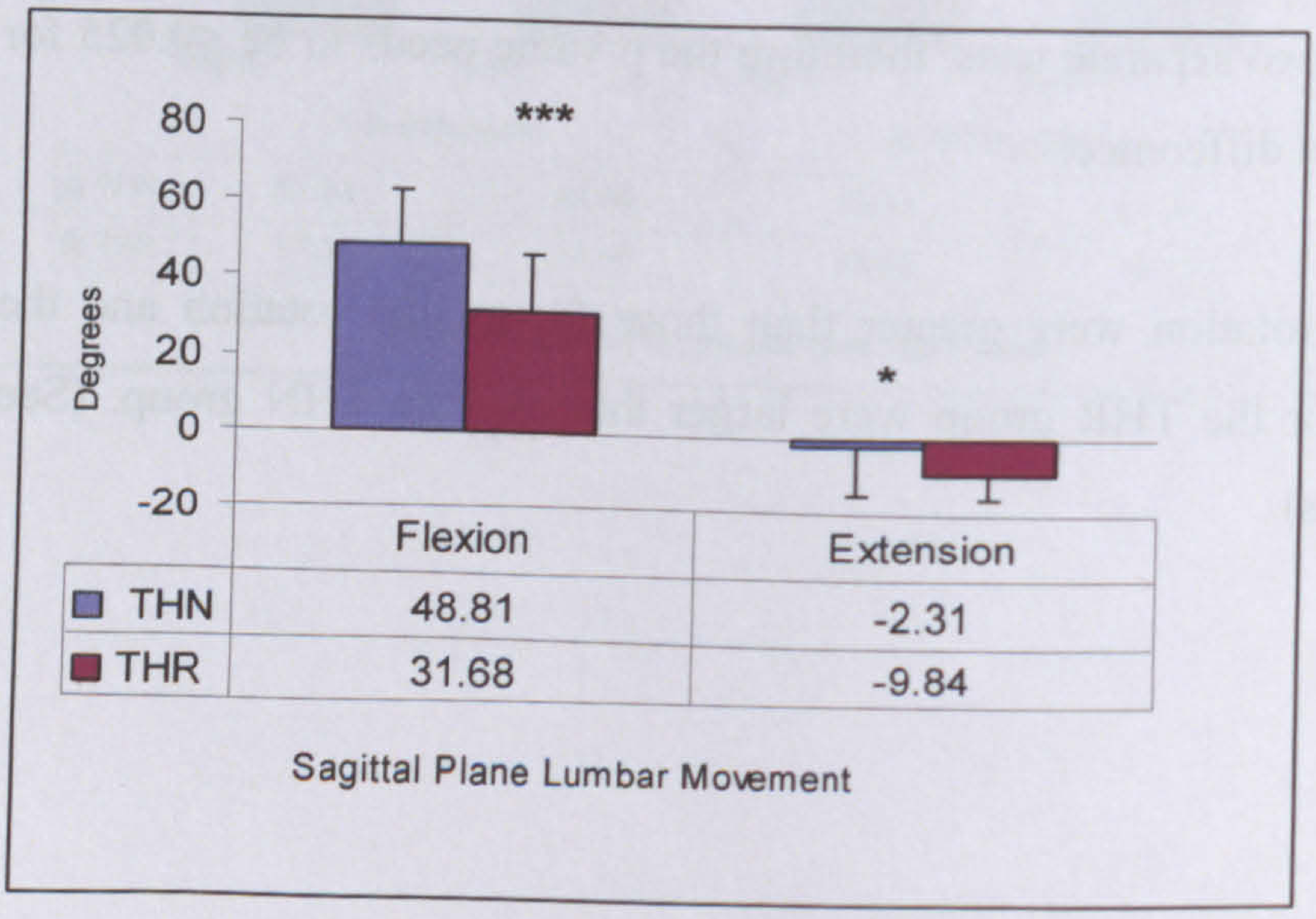


Figure 7.11 Sagittal plane lumbar spine movement comparisons (°) between study groups (n = 24), *** significant difference at p<0.0006, * significant difference at p=0.04

7.2.2. Hip Movement: Clinical measures comparisons for THR group by operation side

When the hip range of motion data for the THR group was analysed by comparing the movement of the operated to the non-operated (good) side, for all movements except hip extension and medial rotation in 70° of flexion, the non-operated hip had more movement. Statistically significant differences were found for hip flexion ($p<0.001$), abduction ($p=0.04$) (Figure 7.9) and lateral rotation in 70° of flexion ($p=0.001$) (Figure 7.10). For hip extension and medial rotation in 70° of flexion, the operated hip had marginally more movement, but this not significant with a mean difference between the sides of 1.04° and 0.61° respectively (See Appendix O for details).

7.2.3 Lumbar Spine Movement: Clinical Measures

Lumbar spine measurement was only undertaken in the sagittal and frontal planes and each planar movement will be presented individually. The raw data can be found in Appendix P (a) and the statistical analysis in Appendix P (b).

7.2.3.1 Sagittal plane movement

The THN group had significantly ($p<0.0001$) more lumbar flexion than those with THR (48.81±3.81° and 31.68±14.78° respectively). The THR group had significantly more extension ($p=0.04$) (-9.84 ±5.85°) compared to the THN group (-2.31±12.63°) (Figure 7.11). Variance in extension range was much larger in the THN group from -21° to 21° compared with -2° to 25° in the THR group. Variance however was greater in the THR group for flexion with a range of 27-74° and from 5-62° in the THN group.

The total arc of sagittal plane lumbar spine motion was significantly ($p=0.039$) greater in the THN group compared to the THR groups (51.2 ±16.72° and 41.52 ±15.59°) respectively.

Figure 7.12 Frontal plane lumbar spine movement comparison (cm) by study groups (n = 24 per group) ** p=0.008, *** p=0.0009

Table 7.10 Lateral lumbar Flexion (cm) comparison of groups for all data (left and right) (n= 48 per group).

	THR	THN
Mean (cm)	12.73	15.84
SD	3.25	2.84
Independent t-test	p<0.0001	

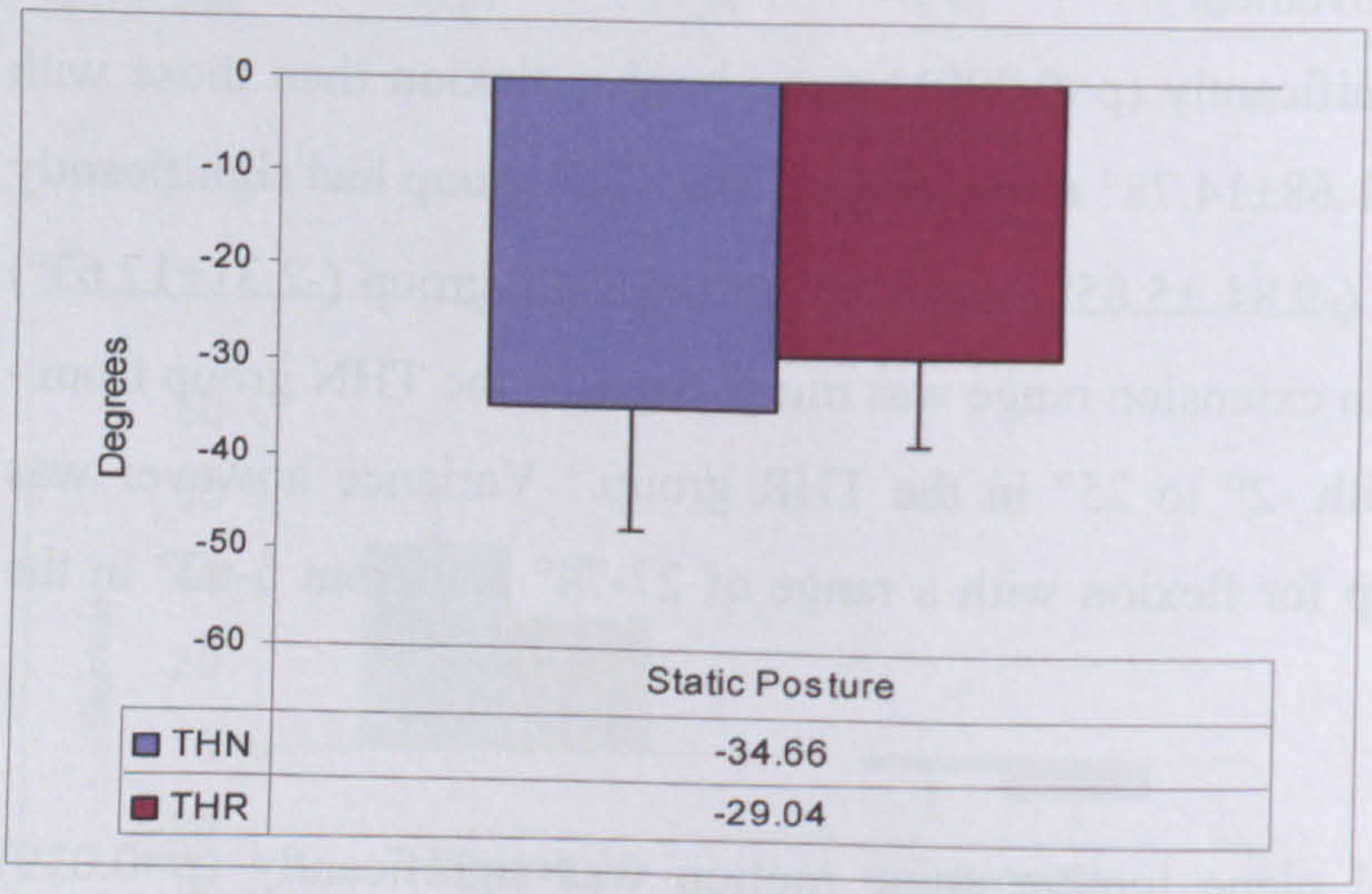


Figure 7.13 Comparison of static lumbar spine posture (°) in standing between the study groups (n=24). No significant difference.

7.2.3.2 Frontal plane movement

As there was a significant difference (p=0.0006) between the groups (THN and THR) for right and left lateral lumbar flexion when tested by one way ANOVA, post hoc t-tests identified these differences to be between the groups for both right (p=0.0009) and left sides (p=0.008) (Figure 7.12). A highly significant difference (p<0.0001) was found between the two groups with the THN group having more lumbar lateral flexion than the THR group, when comparisons were undertaken using all data (Table 7.10).

7.2.3.3 Lumbar Spine posture

The position of the lumbar spine prior to dynamic movement was measured. There was no significant difference between the groups (tested by independent t-test) with the THN group having a slightly larger lumbar lordosis than the THR group (-34.66° & -29.04°, respectively) (Figure 7.13). The THR group showed a greater degree of variability with a higher standard deviation compared to the THN group, 13.10° and 9.19° respectively.

Table 7.11 Comparison of Knee Extension (°) & Flexion (°) between groups and side (n=24).

	THR (°)		THN (°)	
Mean(SD)	Right	Left	Right	Left
Extension	1.04(2.61)	0.83(1.76)	0.96(1.76)	1.00(1.84)
Flexion	126.33(18.18)	127.38(12.62)	134.29(5.32)	133.88(5.17)
Total Extension	0.94(2.21)		0.98(1.78)	
Total Flexion	126.85(15.49)		134.08(5.19) *	
Key: * p=0.003				

7.3 KNEE MOVEMENT

Knee flexion was marginally greater in the THN group but extension was very similar between the groups (Table 7.11) (Raw data and statistical analysis in Appendix Q). Knee range of motion was analysed by both group and side by repeated measures ANOVA for flexion and extension. No significant difference was found in knee extension but flexion was significant by group (p=0.03) but not by side (left vs right). (Table 7.11)

Post-hoc testing by independent t-test, indicated that knee flexion was significantly greater (p=0.003) in the THN group by 7.23° but the THR group had a large standard deviation highlighting the variance in knee flexion for this group. One participant only had 65°of flexion in one knee.

Comparison of knee movement between the operated leg and non-operated leg indicated that there was no significant difference for either knee flexion or extension.

7.4 DISCUSSION OF PHYSIOLOGICAL MOVEMENT

The general data will be discussed before the physiological movement data.

7.4.1 General data

The paucity of research articles on joint movement in patients following THR does not allow much comparison, however Thomas (2003), Trudelle-Jackson et al (2002), Woolson et al (1985) and Murray et al (1975, 1979) have published articles describing physiological movement following THR. Comparison with this research literature using participants with THR will be used to discuss the general data.

In this study the ratio of males to females overall is 1:2.6 and for the THR group specifically 1:3.8, which is slightly higher than the expected ratio of 1:2 or 1:3 for those needing THR (Fear et al, 1997). The male: female ratio for the complete THR operating list from which the participants were taken was 1:4.2 thus the ratio was already skewed from that experienced by other researchers but the sample studied was representative of the hospital population. Chi-square testing indicated no significant difference for the gender numbers in each group. Likewise there was no significant difference in age, height and weight between the two groups thus they were comparable. There were significant differences between genders for height and weight in each of the groups.

The majority of participants (62.5%) had right sided THR surgery and this gives a different proportion to number of left to right THRs compared with other literature using volunteers participants (e.g. Woolson et al, 1985, 52% right). There is no evidence from the literature of variance of recovery in movement or function on the operated side. With regard to previous surgery, the interesting issue is that the four THR group participants who had undergone TKR surgery had this on the opposite side to their hip replacement.

As described by many researchers, for example Keener et al (2003) and Borstlap et al (1994), the entire THR group from this study had good return of function, despite

eight needing a stick for walking outside. No one complained of any difficulties undertaking everyday activities compared to their pre surgery level. There were, however, very different levels of active involvement in leisure activities with the THN group undertaking many more active pursuits. The THR group tended towards more passive hobbies at two years post operation and, as there was no difference in age or weight between the groups, it may be that unwillingness to undertake active pursuits due to pain, hip movement limitation or altered balance pre surgery dictated choice of hobbies. Other medical problems or joint pathology may also limit involvement in activities, for example four people in the THR group had undergone TKR surgery, which may have limited movement ability. The THN group did not have this issue although the group did have people with OA of the hands, feet (n=6) and knees (n=2). Further research needs to be undertaken to ascertain change in socialisation and recreation connected with OA/ THR.

Of the THR group 16.6% had hip pain on the THR side which is comparable to the levels found by McWilliam et al (1996) who recorded 16% of their population having pain at up to 12 months post operation. Kirwan et al (1994) suggest that pain reduction can occur after one-year post surgery but there is no supporting published research (section 2.2.4.1, p 22).

To date there is no published research on back pain in people after THR so it is difficult to evaluate the outcome that 15 participants (62%) in the THR group had low back pain (LBP). Thurston (1985) found that 12 men out of a sample of 20 (60%) with OA hip had back pain and hypothesised that this was exacerbated by the OA hip leading to altered gait mechanics. It is interesting however, that only one person in the matched THN group had intermittent LBP. Numerous issues could cause mechanical low back pain post THR surgery including; change in postural alignment; altered leg length or muscle weakness. The current research did not measure the participants pre-operatively therefore real change in postural alignment at the lumbar spine, hip and leg length cannot be ascertained. There are, however, differences in post-operative spinal posture compared to the THN group which will be discussed later. Muscle weakness was not measured in this study. As no in-depth

information was ascertained about the LBP, this outcome can only be noted and should be addressed in future research.

In the current study the true leg length on the operated side was on average 0.07±0.8cm longer than the non-operated limb, whilst apparent leg length differences showed a mean of 0.23±1.15cm, longer on the operated side. There was no statistical significant difference between the right and left leg lengths for either group or between groups for either true or apparent leg length. Although the results from this study indicate a similar trend, the values are much smaller than those reported by others e.g. Brand & Yack (1996). Likewise Woo and Morrey (1982) measured the leg length of 333 THR patients and found a mean lengthening on the operated side of 1cm, whilst Williamson et al (1977) studied 150 subjects and reported a mean lengthening of 1.6 cm. on the operated side. White & Dougall (2002) report a range of -20mm to +35mm in 200 patients at six months post THR, measured by X-ray. The majority of these patients were within a 10mm difference to the other limb. The variance in research findings may be due to the technique used to measure leg length or to differences in the operating procedure. In this study one surgeon undertook all surgeries and one person measured the leg lengths thus the chance of variation was reduced. In the studies by both Woo & Morrey and Williamson different surgeons and measures were used and this could have resulted in greater differences.

The classification of leg lengths by the operated side being either longer or shorter is more interesting (Table 7.8 p153). There were fewer people with a longer (n=4) operated leg length than shorter (n=12), but the mean differences between the legs (for those with a longer limb,) was higher when compared to the overall mean difference; longer 1.39 ±0.78 cm (n=5), overall mean -0.07± 0.80cm (n=24). The difference in the group with the longer legs skewed the results but as there were more participants (n=11) with a shorter operated leg then this tendency was counterbalanced. Thus those with a longer operated leg could well have altered mechanics at the hip and lumbar spine to accommodate for this length change. Gofton & Trueman (1971) suggest that pre OA leg length may play an important part in the pathokinesiology of OA. Of the 36 leg lengths with idiopathic OA that they

assessed, 33 had disease on the lengthened side. Although Brand & Yack (1996) demonstrated a low correlation to back pain this has not been clearly shown for leg length differences of less than 2cm, suggesting that small alterations in leg length as a result of surgery my not be a key factor.

7.4.2 Physiological data

The results for hip movement will be discussed before those of the lumbar spine. Comparison with the limited published literature on passive physiological data at two years post total hip replacement will be undertaken where possible. Range of motion data from those without hip surgery will also be used for comparison as it could be hypothesised that at two years post surgery patients should have stabilised.

7.4.2.1 Hip movement

The findings from the healthy group in the present study are similar to those by James and Parker (1989) for a group of healthy 70-74 year olds without THR surgery, indicating that all participants had good hip movement comparable to that found by other researchers using participants within same age band.

Hip rotation in the THN groups was slightly lower than the results of Hamill & Knutzen (2003) and Kapandji (1989) (Table 3.1, p36A), who looked at a younger adult population. The higher range of hip rotation in flexion for the THN group, compared to those studied by James & Parker (1989), may be due to the level of activity and fitness of the current study group or the position of measurement. The majority of the present participants were involved in some degree of sporting activity including swimming, badminton and walking and this may have influenced the results. The THR group had less hip rotation both lateral and medial when compared to the James and Parker study but this is not unusual, given their surgery. Extension and adduction were not measured in the James and Parker study so these measures cannot be compared.

Comparison between the groups

It is unsurprising that the participants in the THR group had a lower range of hip motion in all planes when compared to the THN group, given the surgery they have undertaken and their relative inactivity. There were highly significant differences in motion for hip flexion ($p<0.00001$), extension ($p<0.00001$), lateral rotation ($p<0.0001$) and medial rotation ($p<0.0001$). For abduction ($p=0.04$) and adduction ($p<0.001$) the probability of the results being caused by chance was greater but still significant. In comparison with the work of Murray et al (1975); Woolson et al, (1985), Trudelle-Jackson et al (2002) and Thomas (2003), as mentioned in section 3.1.3, the THR group results obtained in this study indicate greater range of motion particularly when related to Thomas's work.

Taking the results of Woolson et al (1985) at two years after surgery the THR group from this present study demonstrate similar results for flexion (91.5°) compared to (96.75 ±16.27°) respectively. However the other results for abduction (27.58 ±8.93°), adduction (24.25 ±10.96°) medial (21.04 ±13.87°) and lateral rotation (30.54 ±13.93°) are markedly greater than those of Woolson et al (1985) (19°, 15.4°, 4.9°, 18.5° respectively) but similar to Trudelle-Jackson et al (2002) (93.7°(Flexion), 23.9°, 18°, 24.1°, 21.2°, respectively). Interestingly these measures all increase in the Woolson study at the mean 7.5 year follow up and are then comparable to the physiological measurement taken at the two year mark for this present study. At two years post surgery Murray et al (1975) noted significant loss of extension (-25°) although recovery of all other movements had occurred with the greatest loss in those with bilateral replacements. These results may be explained by the type of operative procedure used and the measurement method, but unfortunately these details are not given in the Trudelle-Jackson et al (2002) or Woolson et al (1985) study.

At six months after surgery, the post THR population studied by Thomas (2003) had hip flexion of 83 ±11°, abduction of 34 ± 8° and extension of 10 ± 10° compared to the results of this research 99.4 ±15.9°, 30.3 ±9.9° and 0.48 ± 3.9° respectively. Both flexion and abduction passive physiological movement were greater in the current study population but extension was considerably less. Both studies used a

universal goniometer and followed the guidelines of Norkin and White (1995). The difference in extension is difficult to explain; differences could arise from three sources: the degree of hip flexion contracture prior to surgery, the type of surgery and incision placement being undertaken (both of these are unknown in the Thomas and Woolson et al, study populations) or the measurement technique which may have been different even if following the guidelines of Norkin and White (1995). The Thomas (2003) study assessed hip extension in side lying, whilst the current study used supine lying. Difficulty in localising pelvic movement in side lying may have given rise to the larger degree of hip extension found by Thomas (2003).

One of the greatest contributors to limited movement in the early post surgery period is restriction due to limited soft tissue pliability around the new hip joint (Charles et al, 2004). This may be a consequence of the pre operative soft tissue contractures of more than 20° which had not been released at surgery (Longjohn & Dorr, 1998). If the soft tissue is not balanced at or around the hip joint then limited movement may be a post operative complication resulting in a delayed return to full movement (Charles et al, 2004, Longjohn & Dorr, 1998). These authors highlight the importance of the surgeon testing for full hip extension, abduction and knee extension during surgery to ascertain if surgical release of tight tissue is required.

The population in this present study had very little recovery of hip extension (mean 0.48°). It may be hypothesised that either they did not have adequate soft tissue balance at time of surgery or that for some reason their hip extension reduced over time. The latter reason goes against the evidence from Thomas (2003) who clearly showed that hip extension increases with time, albeit at a slower rate than other physiological movements. Although the anterior hip structures get stretched through the later stance phase of gait, it may be that the pelvic position counteracts this effect or that these patients were not actively encouraged to exercise into extension during rehabilitation.

The lack of hip extension is a potential ongoing problem as there may be implications for gait mechanics. Lee et al (1997) studied the dynamic implications of

loss of hip extension showing that the degree of flexion contracture (Thomas test) correlated significantly ($p<0.0001$) with peak hip extension during walking. The results of the Thomas test also correlated with mean anterior tilt of the pelvis ($p<0.0086$). The closest significant correlation was between peak hip extension during walking and peak anterior pelvic tilt ($p<0.00001$). The mean standing pelvic tilt angle was 27 ±11° as opposed to 15 ±11° during walking, showing that the anterior structures can be stretched during walking or that the body compensates for lack of extension by either tilting the pelvis or flexing the ipsilateral knee.

When the operated hip movements from the THR group were compared to those of the non-operated side (section 7.2.2, p153) the operated hips had less movement. There was a significant decrease in flexion ($p<0.001$), abduction ($p=0.004$) and lateral rotation in 70° of flexion ($p=0.001$). Hip extension and medial rotation in 70° of flexion, on the operated side had marginally more movement than the non-operated side, but this not significant with a mean difference between the sides of 1.04° and 0.61° respectively.

There is limited research on whether the range of hip movement on the operated side reaches equivalence to the non-operated side. Woolson et al (1985) found that hip movement changed up to a mean of 7.5 years after THR surgery and this may be the case for the present patient population. Although hip movement was significantly less for flexion, extension and lateral rotation compared to the non-operated side, improvement of movement may take longer to be established. As the THR group were all moderately active it is not known if this altered movement and affected their lifestyle. Set alongside limited hip extension, decreased movement at the hip may help to explain the cause of the back pain which was present in 62.5% ($n=15$) of the THR group.

7.4.2.2 Lumbar Spine Movement

As there is no other published research on physiological spinal motion after THR, the discussion will highlight the possible underlying reasons and hypotheses for the

results. A comparison of results from general published research will be undertaken first and then comparisons between the groups.

In comparison with published research on range of lumbar spine physiological measurements from a comparable healthy age group, the population from this present research showed equivalency for the THN group flexion (van Herp et al, 2000 and McGregor et al, 1995, Table 3.8, p54A) and lateral flexion (Mellin, 1986b). Extension for the present population (2.31±12.63°) was very limited compared to that found by van Herp et al (2000) or McGregor et al (1995) mean of 16.0° and 14.6° respectively. Four of the THN group had restricted lumbar spine extension (Appendix P). As they did not complain of any pain in their spine and had not noticed any limited movement their results were left in the calculations. If the data from those with limited extension was removed from the THN group, mean extension became -7.4±8.7°, which is comparable to the THR group but still less than the literature. Although normal distribution of the data was found, this was a relatively small sample and further research on greater numbers may be useful to ascertain if the population in this study were unusual.

The THR group had less lumbar spine flexion (31.69°/ 48.81°) and lateral flexion (12.73°/ 15.84°), but more extension (-9.84°/ -2.31°) compared to the THN data, and their results for extension were nearer the norm than in the THN group (-9.84 ±5.85°).

Comparison between the groups

Lumbar spine flexion ($p<0.0001$) and lateral flexion (not significant) were limited in the THR group compared to the THN group. Extension ($p=0.04$) and static posture were both slightly greater in the THR group. All measurements were taken by the same person with the same tool giving good reliability, however this is a relatively small sample and the results cannot be extrapolated to a wider population.

The total arc of sagittal plane movement for the THN group was significantly greater than that in the THR group (mean 51.2° and 41.5° respectively). The significant

greater degree of flexion in the THN group (17.2°) is surprising at this stage in the recovery of the THR patients. As the THR group still had significantly limited hip movement post surgery, it was hypothesised that the THR group would have more lumbar flexion and more knee flexion to compensate for the lack of hip movement but this was not the case. As general lumbar spine movement was reduced in the THR group compared to the THN it may be that this group had some general joint pathology which limited their movement or that the THN group were just more active and their more active lifestyle (see section 7.1.5, p149) helped them to maintain their general movement.

Imbalance in flexion and extension motion between the two groups could be partly explained by the lumbar posture position. As the THN group have an exaggerated lumbar lordosis, their range of lumbar flexion would appear to be greater as they are starting from a more extended posture. Conversely the THR group held themselves in a slightly less extended position so had less flexion and more extension. However the difference in flexion (17.13°) between the 2 groups is much greater than that of extension (7.53°), so this hypothesis does not give a full explanation.

The total arc of motion is influenced by the four participants in the THN group who have less spinal movement but did however have a reduced lumbar lordosis on the static posture measures. On further examination of their results it may be that assessment of their thoracic spine movements would have revealed interesting data. Another explanation concerns identification of the spinal markers at the full range of flexion and extension. Excellent reliability of lumbar spine physiological measurement on young active participants was shown (Appendix D) and may need further investigation to ensure accuracy and reliability in an older age group. Mellin (1986a,b) amongst others have shown that the measurement of lumbar extension is less reliable than all of the other lumbar movements (section 4.2.1.2, p69). Pearcy et al (1984) noted that the $L_{1/2}$ segment level had greater individual extension compared to the rest of the lumbar spine if the measurements for some individuals were taken from a point slightly above the T_{12} level then a larger degree of extension may have been recorded. This might explain the different data in the THN group.

Although the results from this study show trends in lumbar spine motion this is only part of the spinal story, further research including thoracic spine measures are needed to address this issue. Haideri et al (1997) amongst others suggest that all segments of the spine need to be evaluated so that the results from individual segments are observed as part of the whole.

7.5 SUMMARY OF PASSIVE PHYSIOLOGICAL DATA

Summary of the passive physiological data

- THR group had significantly less hip flexion ($p<0.0001$), extension, abduction, adduction ($p= 0.0002$) & lateral and medial rotation.

- THR group had significantly less lumbar spine flexion and lateral flexion but more extension. They also had a slightly reduced lumbar lordosis in standing but this was not significant.

- THR group had significantly less knee flexion than the THN group.

Discussion on the correlation between static clinical and dynamic measures will be undertaken at the end of Chapter 8.

8.0 BIOMECHANICAL DATA AND ANALYSIS

8.1 BIOMECHANICAL GAIT DATA

Analysis of movement data for the hip, pelvis and lumbar spine has been undertaken by: range of movement for each of the segments, angle/angle diagrams to analyse patterns of movement interaction between the segments, hip joint moments, and timing of the movement. Discussion of the results will be given in (Section 10.0).

A minimum of five walking trials per side were collected for each of the 52 participants who undertook full gait analysis. The data were processed in Kinemetrix software and then transferred to Vicon software 'Workstation' for identification of gait events and review before being processed through the Plug in model in BodyBuilder and collated through Polygon software. 26 participants started the study but kinetic data from one participant was incomplete and another participant was excluded from the study, due to an injury which occurred after agreeing to take part in the study, these data was excluded from the calculations. The data on the remaining 48 study participants (24 in each group) will be presented.

Three good walking trials were achieved for each side for 23 of the THR and 23 of THN group. One trial per group the force plate data was not readable and for another the markers were not clearly seen, so for 2 participants only 2 sets of walking data were acceptable instead of three. Data was deemed acceptable if the error margin on hip rotation was less than 5° (Baker et al, 1999). Data for the control group were collected by right and left side (THN) and presented collectively as there was no significant difference between these data sets (Appendix R: hip, S: pelvis, T: lumbar spine), and the hip replacement group by the operated (THR op) and non operated sides (THR non op), separately. Group variation of joint motion through the gait cycle is presented in Appendix X, and will be used to enhance the discussion.

Through the presentation of this data phases of gait, heel strike (initial contact), loading response, mid stance, terminal stance, toe off (pre-swing), initial swing, mid swing and terminal swing will be used as described in section 4.4.

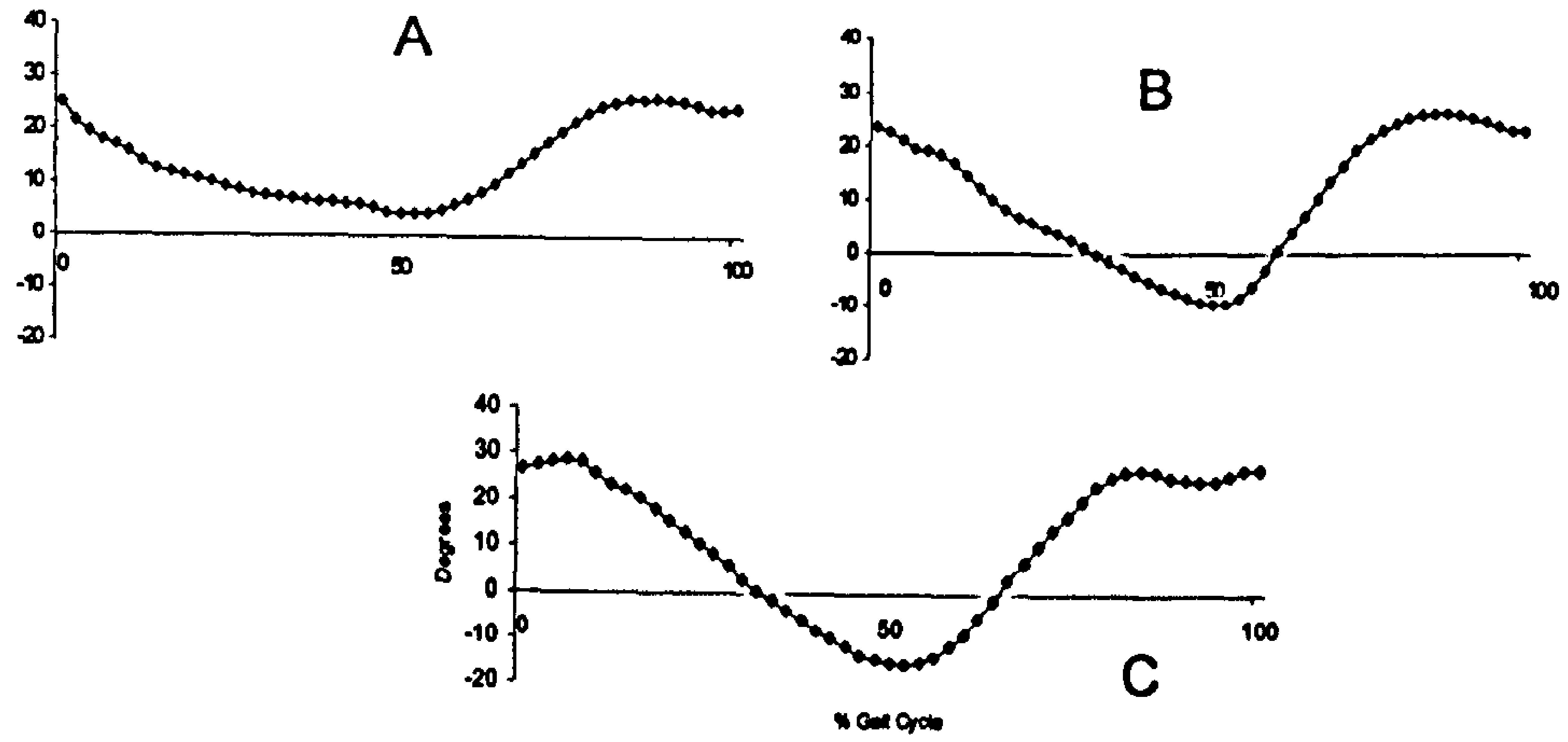


Figure 8.1 Sagittal Plane Hip Movements; individual angle time graphs; +ve on y axis = flexion
A= THR OP
B = THR Non OP
C = THN

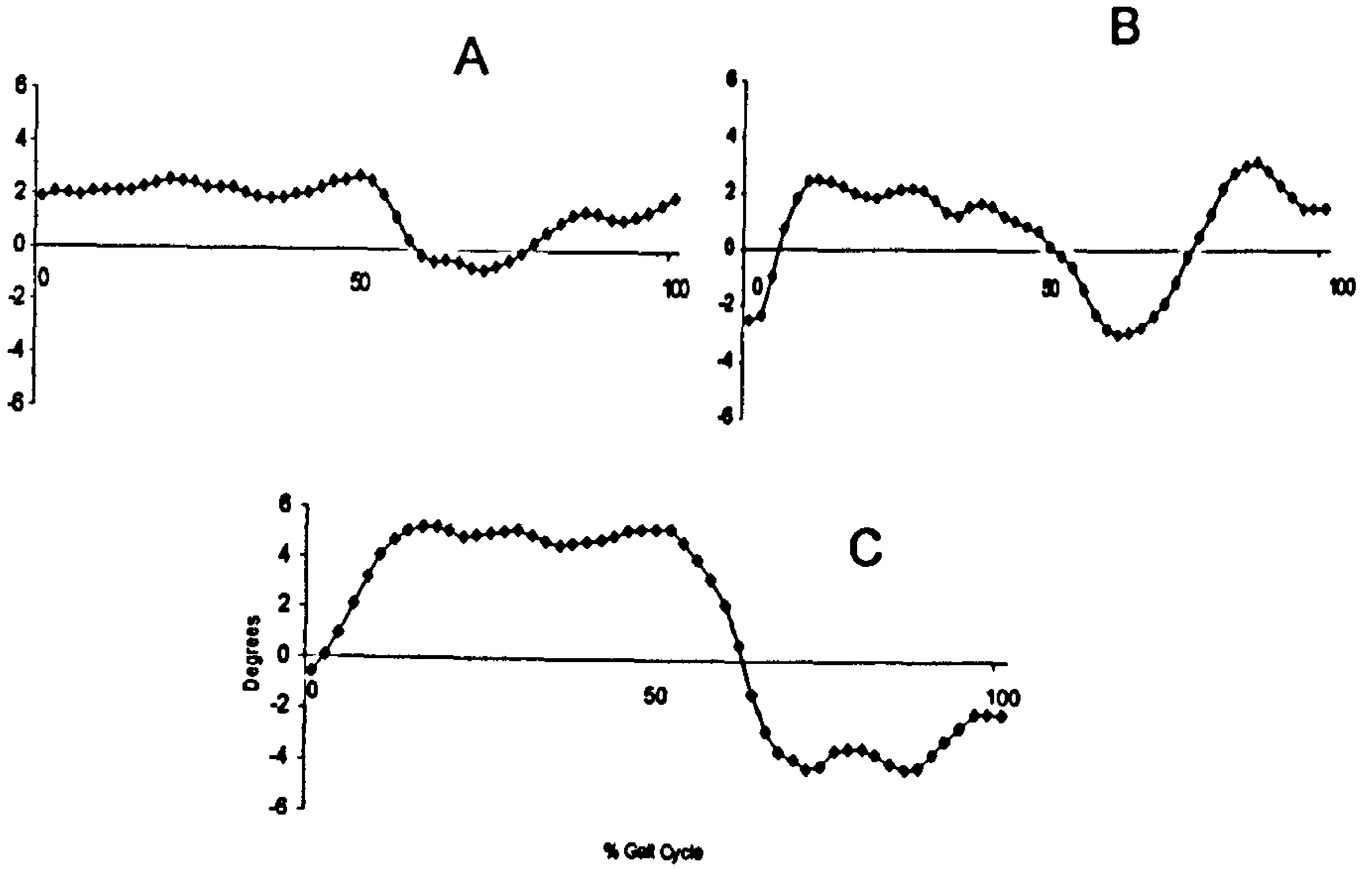


Figure 8.2 Frontal Plane Hip Movements; individual angle time graphs, +ve on y axis = abduction
A= THR OP
B = THR Non OP
C = THN

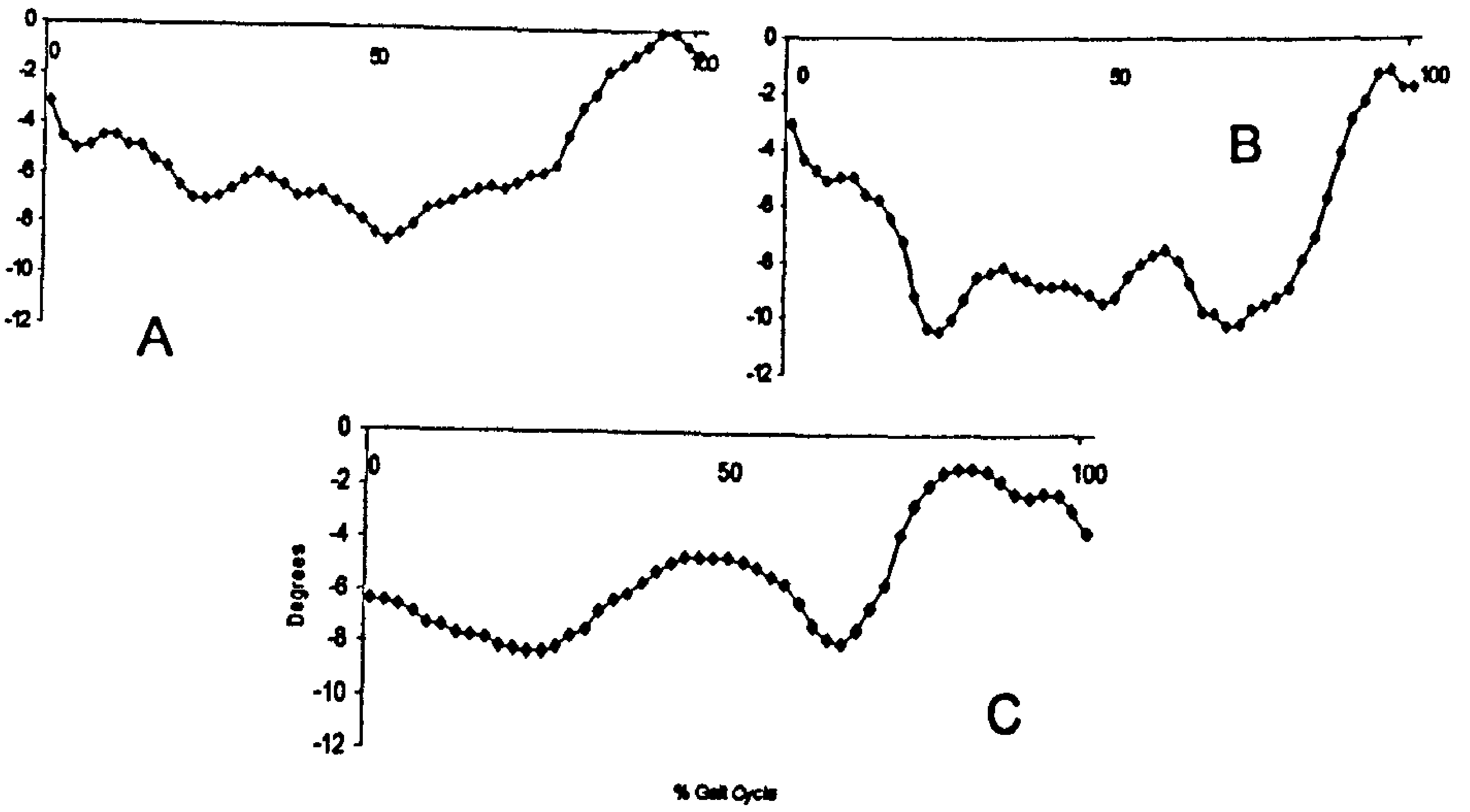


Figure 8.3 Horizontal Plane Hip Movements; individual angle time graphs, +ve on y axis = medial rotation
A= THR OP
B = THR Non OP
C = THN

Time is represented as 100% of the gait cycle is on the x (abscissa) axis and degrees of motion on the y (ordinate) axis for all three figures.

8.2 RANGE OF MOTION - HIP

For all hip movement graphs, the positive direction for the sagittal plane represents flexion, in the frontal plane, abduction, and in the horizontal plane, medial rotation. Mean data per group is represented in Appendix R. Tests for normal distribution and statistical analysis of the mean data is also presented in Appendix R.

8.2.1 Individual hip data graph

Representative angle time graphs for each of the groups are displayed in Figures 8.1 - 8.3. Examples of each hip movement curve from one individual from each of the groups during gait for each hip movement in each plane: sagittal, frontal and horizontal. These individuals are representative of their respective group. Time is represented as 100% of the gait cycle is on the X (abscissa) axis and degrees of motion on the y (ordinate) axis. Each graph starts at initial/ heel contact. Patterns of movement between the groups will be discussed when the averaged curves are presented in section 8.2.3.

8.2.2 Averaged hip angle time graphs per individual

Hip data from each person was then averaged over the three gait cycles recorded. Representative averaged graphs from one person for each of the groups for each of the movements, in the sagittal, frontal and horizontal planes are presented in Figures 8.4 - 8.6, (p168 (sagittal plane) and p168A (frontal and horizontal)). Mean data is represented by the mid line in each graph with the lines on either side denoting one standard deviation.

Standard deviations for the sagittal plane are small but these increase for data in the frontal and horizontal planes. Variability between groups and planes will be presented in section 8.2.4.

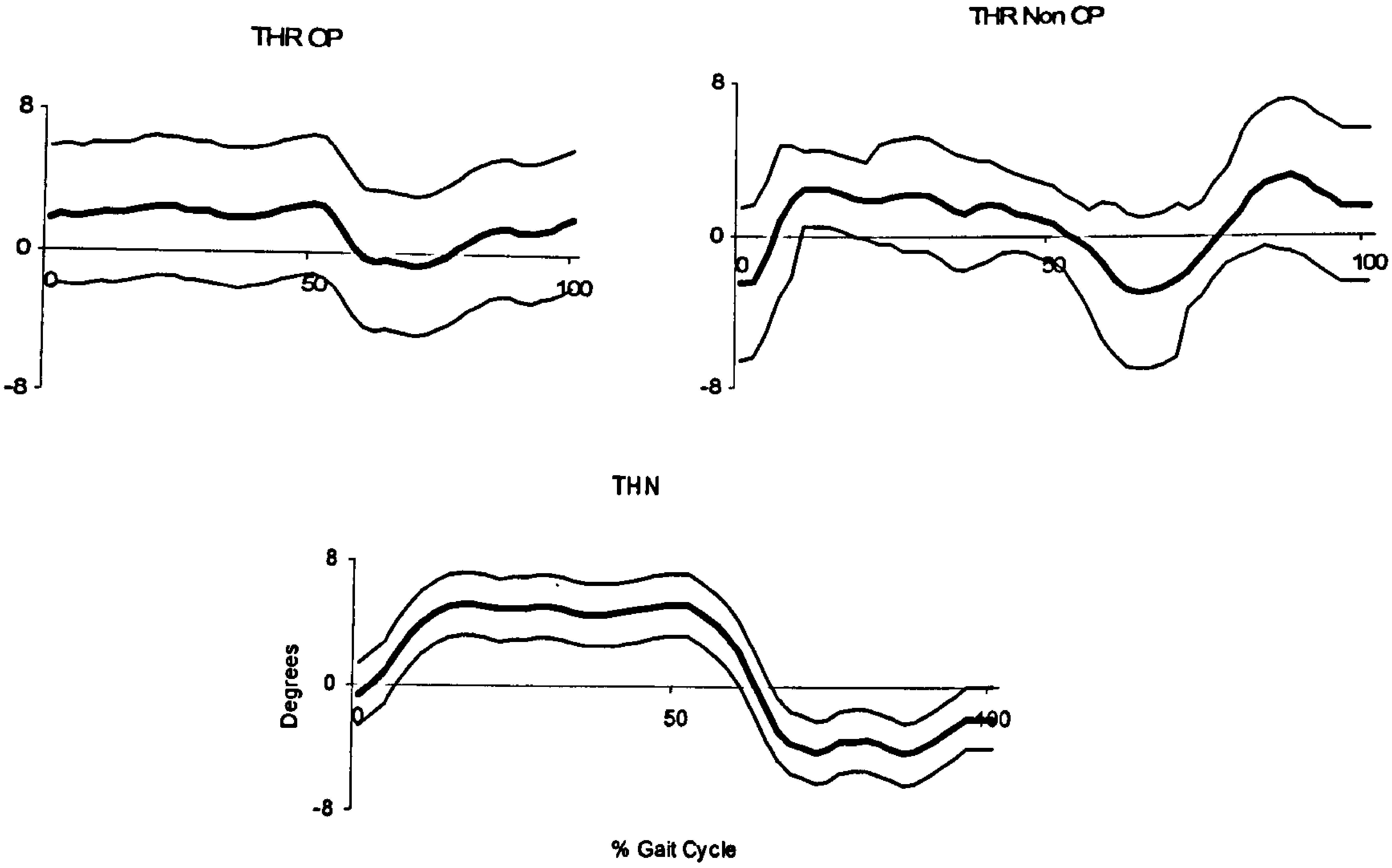


Figure 8.5 Frontal Plane Hip Movements; average of three walking trials for one person with standard deviations, Time is represented as 100% of the gait cycle is on the x (abscissa) axis and degrees of motion on the y (ordinate) axis; +ve = adduction.

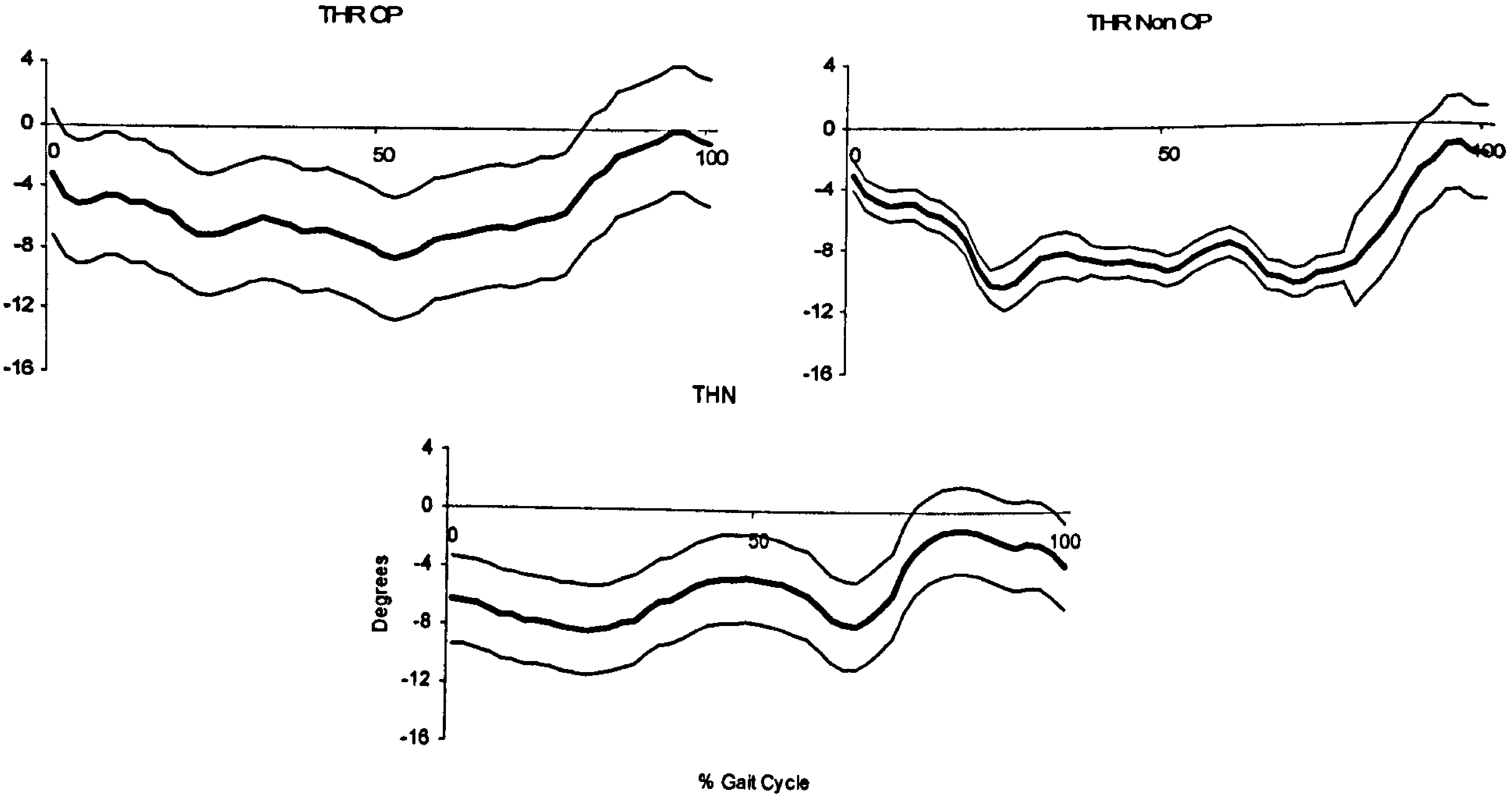


Figure 8.6 Horizontal Plane Hip Movements; average of three walking trials for one person with standard deviations, time is represented as 100% of the gait cycle is on the x (abscissa) axis and degrees of motion on the y (ordinate) axis; +ve = medial rotation.

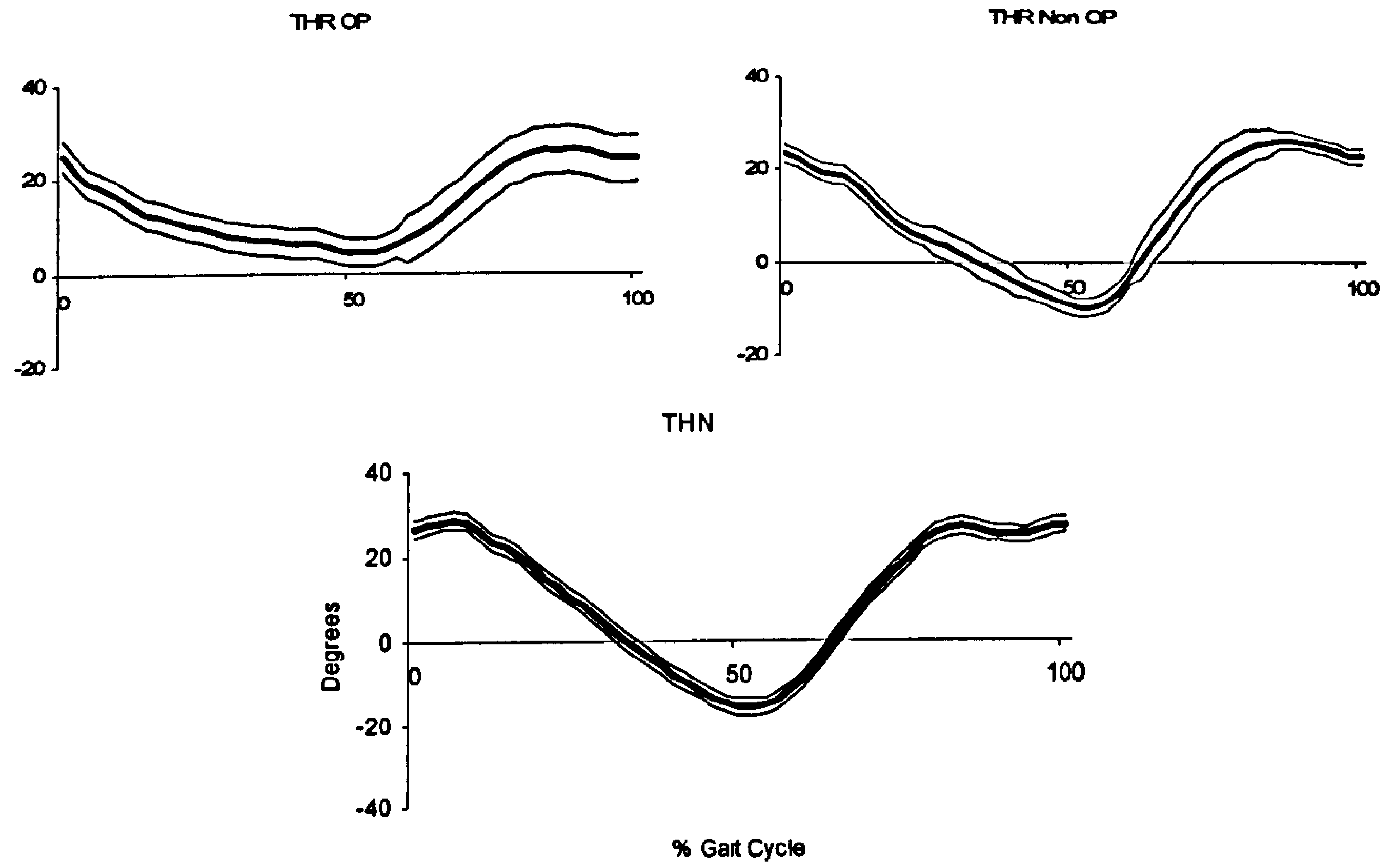


Figure 8.4 Sagittal Plane Hip Movements; average of three walking trials for one person with standard deviations, ordinate (y) axis (Degrees of motion), +ve = Flexion, abscissa (x) axis % gait cycle.

8.2.3 Averaged hip data per group

Averaged data from each individual for each movement were then collated and averaged for the group for each of the sagittal, frontal and horizontal plane. The movement cycle for each group was compared against those of the other groups.

Averaged hip movements per group in each plane can be seen in Figures 8.7 – 8.9 (p170A) with time represented as 100% of the gait cycle on the X axis and degrees of motion on the y axis. In the sagittal plane (Figure 8.7) positive values represent hip flexion and negative values hip extension. The hip is in flexion at the start of the gait cycle (P1, Figure 8.7) with the THN group having the greatest value and the THR op side the least. The hip moves into maximum extension at the end of the stance phase (P2, Figure 8.7) for each of the groups with the THR op side having the smallest degree of extension and the THN group the largest. The hip returns to flexion towards 78% of the gait cycle (P3, Figure 8.7). All the groups have a similar pattern of movement but the extremes of the cycle appear to be different between the

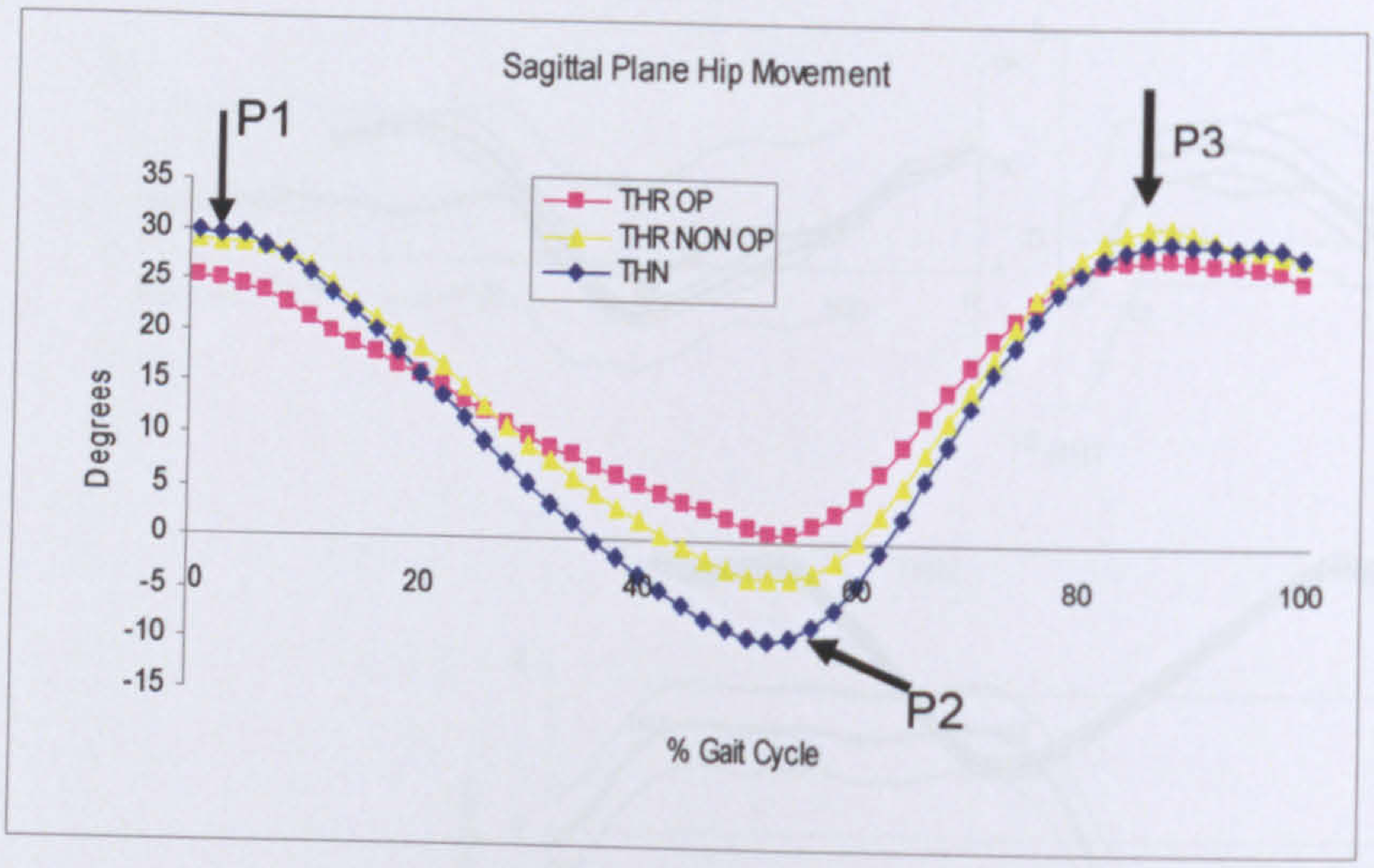


Figure 8.7 Sagittal plane hip movements; averaged graph for each group, +ve on y axis = flexion

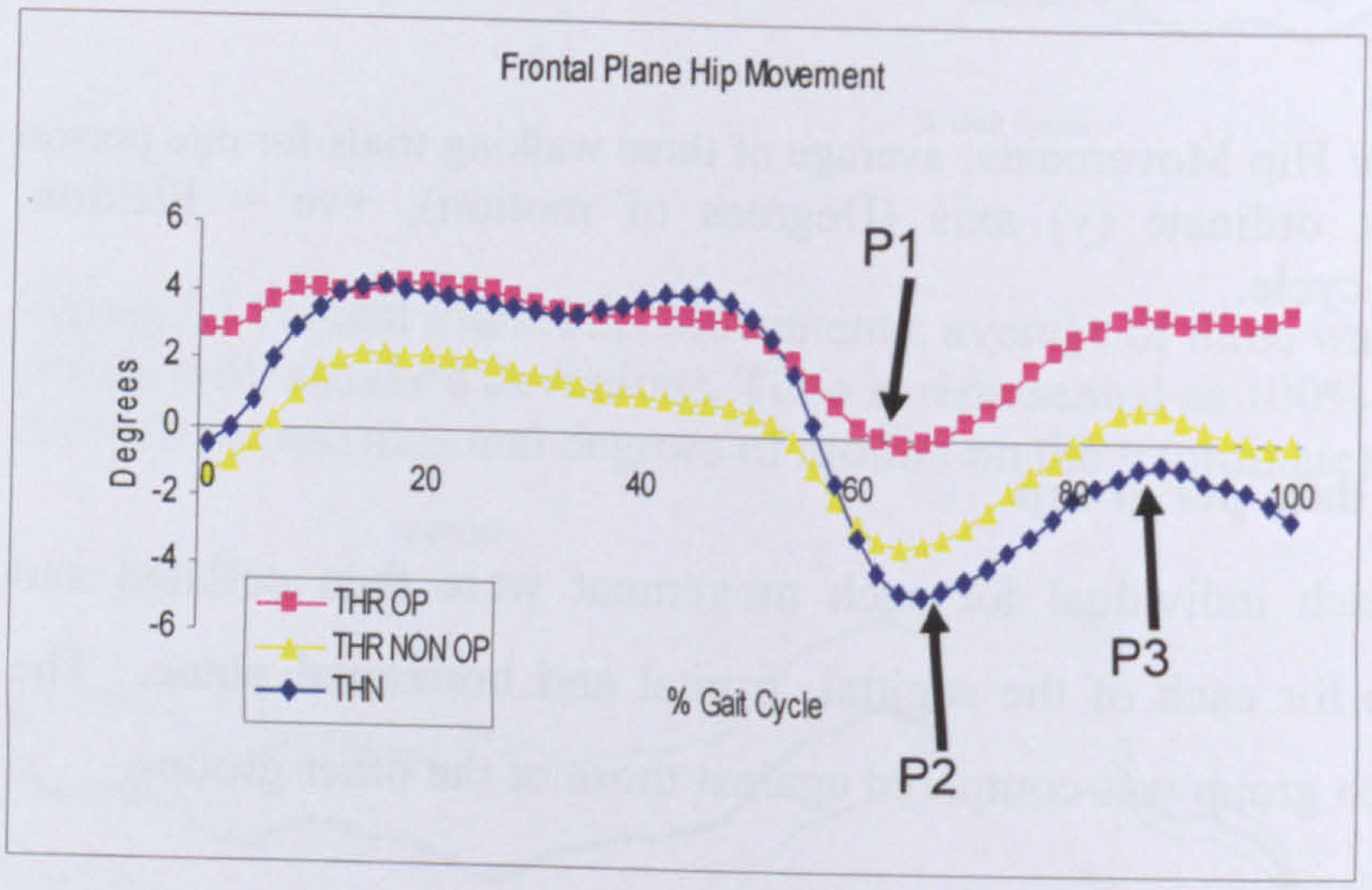


Figure 8.8 Frontal plane hip movements; averaged graph for each group +ve on y axis = adduction

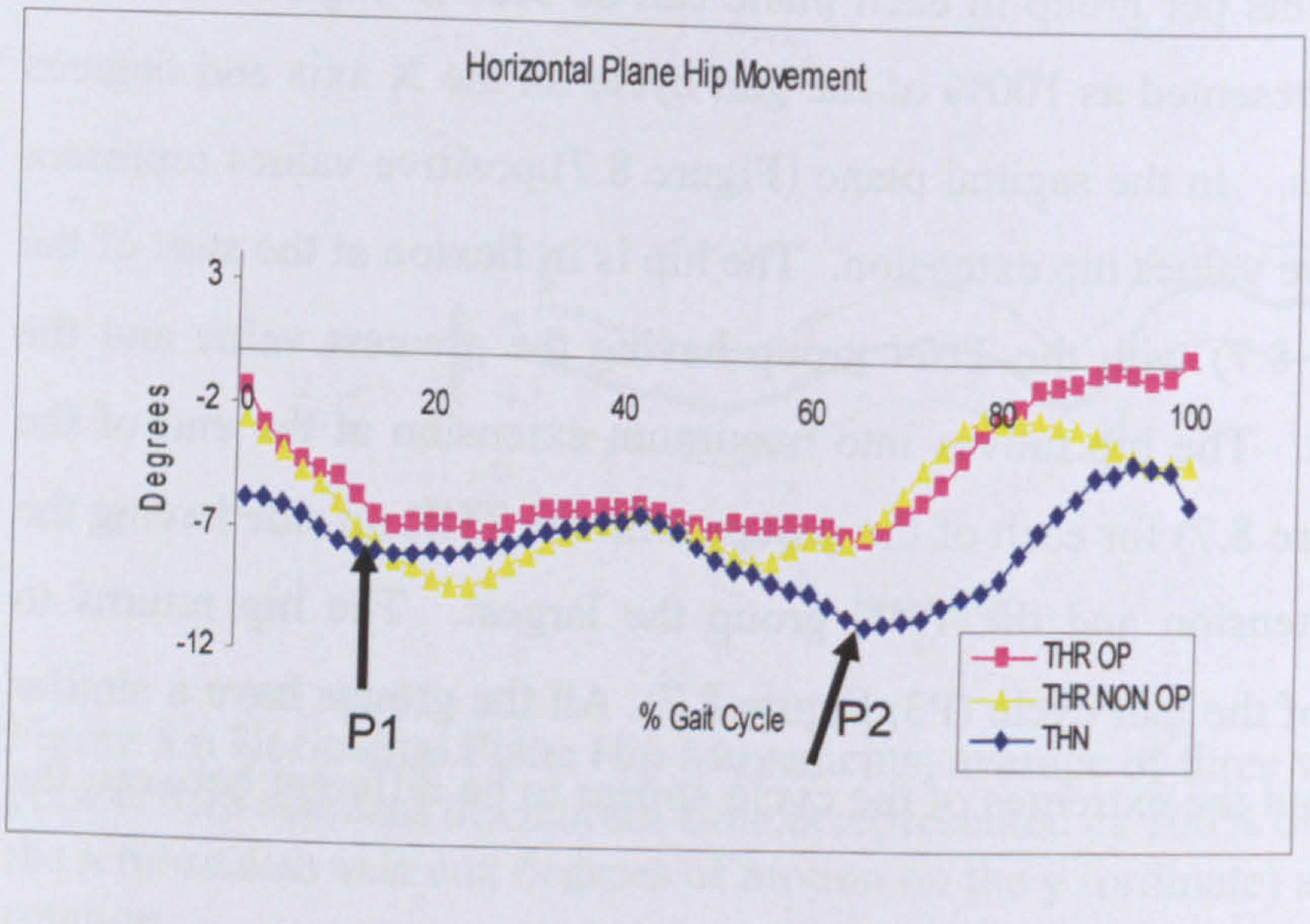


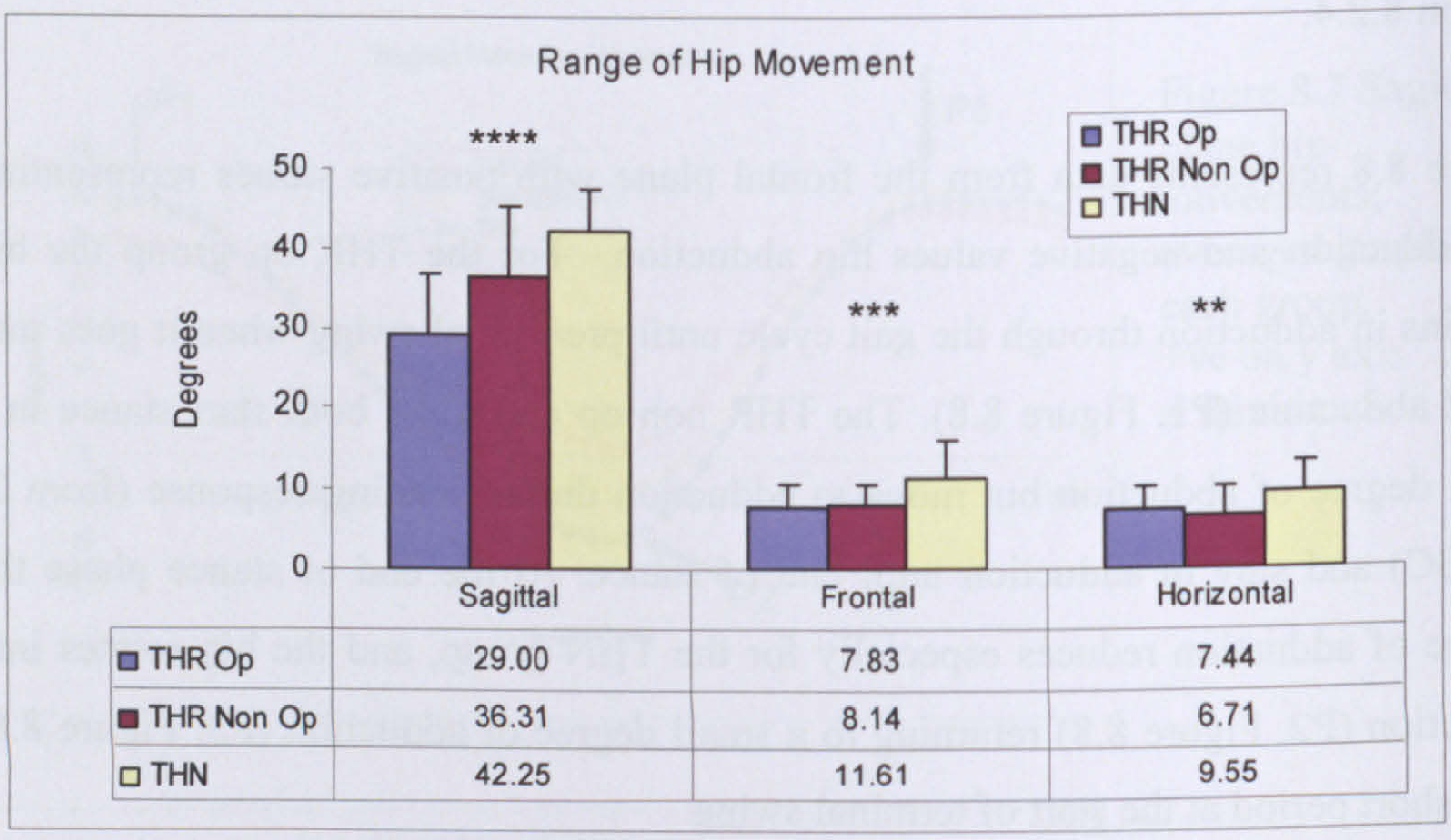
Figure 8.9 Horizontal plane hip movements; averaged graph for each group +ve on y axis = medial rotation

groups. Comparison of data from specific points in the gait cycles will be given in section 8.2.4.

Figure 8.8 represents data from the frontal plane with positive values representing hip adduction and negative values hip abduction. For the THR op group the hip remains in adduction through the gait cycle until pre/ initial swing when it goes into slight abduction (P1, Figure 8.8). The THR non op and THN both start stance in a small degree of abduction but move to adduction during loading response (from 2-8% GC) and stay in adduction until end of stance. At the end of stance phase the degree of adduction reduces especially for the THN group, and the hip rotates into abduction (P2, Figure 8.8) returning to a small degree of adduction (P3, Figure 8.8) for a short period at the start of terminal swing.

The THR non op group has less adduction than the THN group and starts to reduce adduction much earlier and to a smaller degree than the THN group. All the groups demonstrate a similar movement pattern but the THR op group appears to maintain hip adduction at all times by a constant degree when compared to the THR non op group. When comparing the THR non op with the THN group, the curves are similar overall but the THR non op group does not have the same magnitude of adduction nor maintain the second adduction peak at the end of stance phase resulting in the early release into hip abduction mentioned earlier. The THN group appears to have a more dramatic change in movement that either of the other groups especially the THR op group. Comparisons of this data at key points in the gait cycle will be given in section 8.2.4.

Movement during gait in the horizontal plane is represented in Figure 8.9 positive values represent medial rotation of hip and negative hip lateral rotation. For all groups the hip remains in lateral rotation throughout the gait cycle, with the pattern of movement being similar for the THR op and non op groups but these are different to that of the THN group. For the THN group lateral rotation increases at loading response (P1, Figure 8.9) until mid stance when it reduces to its smallest amount at the start of terminal stance. The hip slowly increases lateral rotation to a maximum



	Sagittal	Frontal	Horizontal
▨ THR Op	29.00	7.83	7.44
■ THR Non Op	36.31	8.14	6.71
☐ THN	42.25	11.61	9.55

Figure 8.10 Averaged overall range of movement for each group; Sagittal, Frontal and Horizontal Plane Hip Movements, **** $p<0.0001$, ***$p=0.0003$, ** $p=0.005$

Table 8.1 Statistical Tests for Post hoc testing for averaged hip range of movement data

Plane	THR op vs THR non op ≈	THR op vs THN ≡	THR non op vs THN ≡
Sagittal	p=0.002	p<0.0001	p=0.008
Frontal	NS	p=0.001	p=0.002
Horizontal	NS	p=0.037	p=0.002

Key:
THR op:- Operated side of the THR group
THR non op:- Non operated side of the THR group
THN:- control group (R& L data combined)
NS:- Not significant
≈ tested by a paired t-test, ≡ tested by a non paired t-test

at initial swing (P2, Figure 8.9) when lateral rotation reduces sharply. For the other groups there is less movement overall and the dip into a larger degree of lateral rotation during stance is seen only in the THR non op group but this is delayed compared to normal until well into midstance. The THR op group moves to neutral rotation at the end of swing phase whilst the THR non op group remain in lateral rotation.

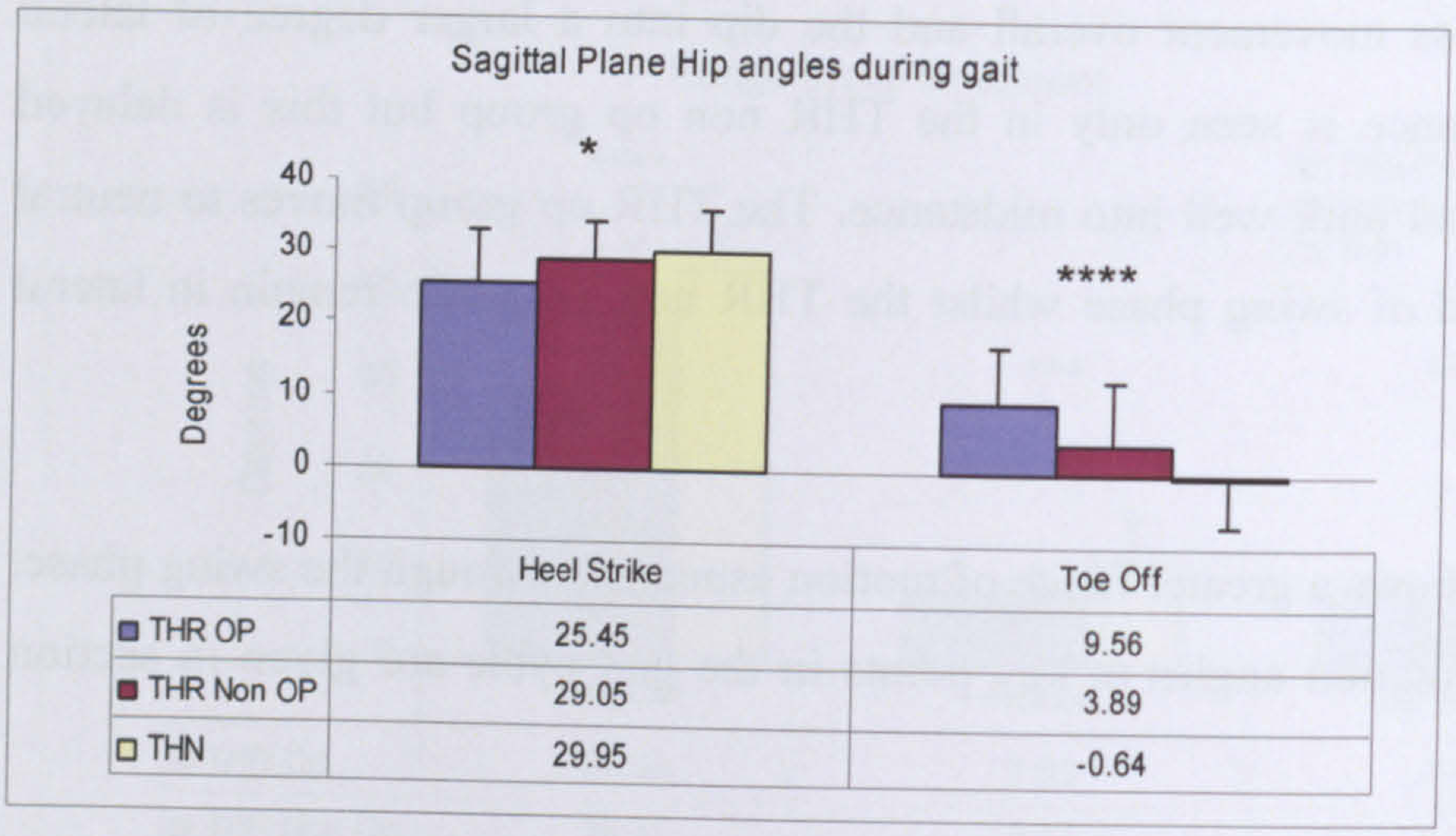
The THN group shows a greater range of motion especially through the swing phase. Comparisons of rotation angles at key points in the gait cycle are given in section 8.2.4.

8.2.4 Mean hip range of movement data

To assess the statistical variance in the data sets between groups the data range from each person was averaged for sagittal, frontal and horizontal plane movement. A summary of this data can be found in Figure 8.10. The data in all three planes was significantly different between the three groups when tested by one way ANOVA. The most significant difference in range was in the sagittal plane with the THN having the largest range and the THR op group the smallest, significant at $p<0.0001$. The results of post hoc testing by paired and non paired t-test are shown in Table 8.1. Taking into account appropriate Bonferroni correction where significance is taken at $p<0.013$ all the sagittal plane range tests reach significance, with the most noteworthy being the operated side with the control group (THR op vs THN, $p<0.0001$).

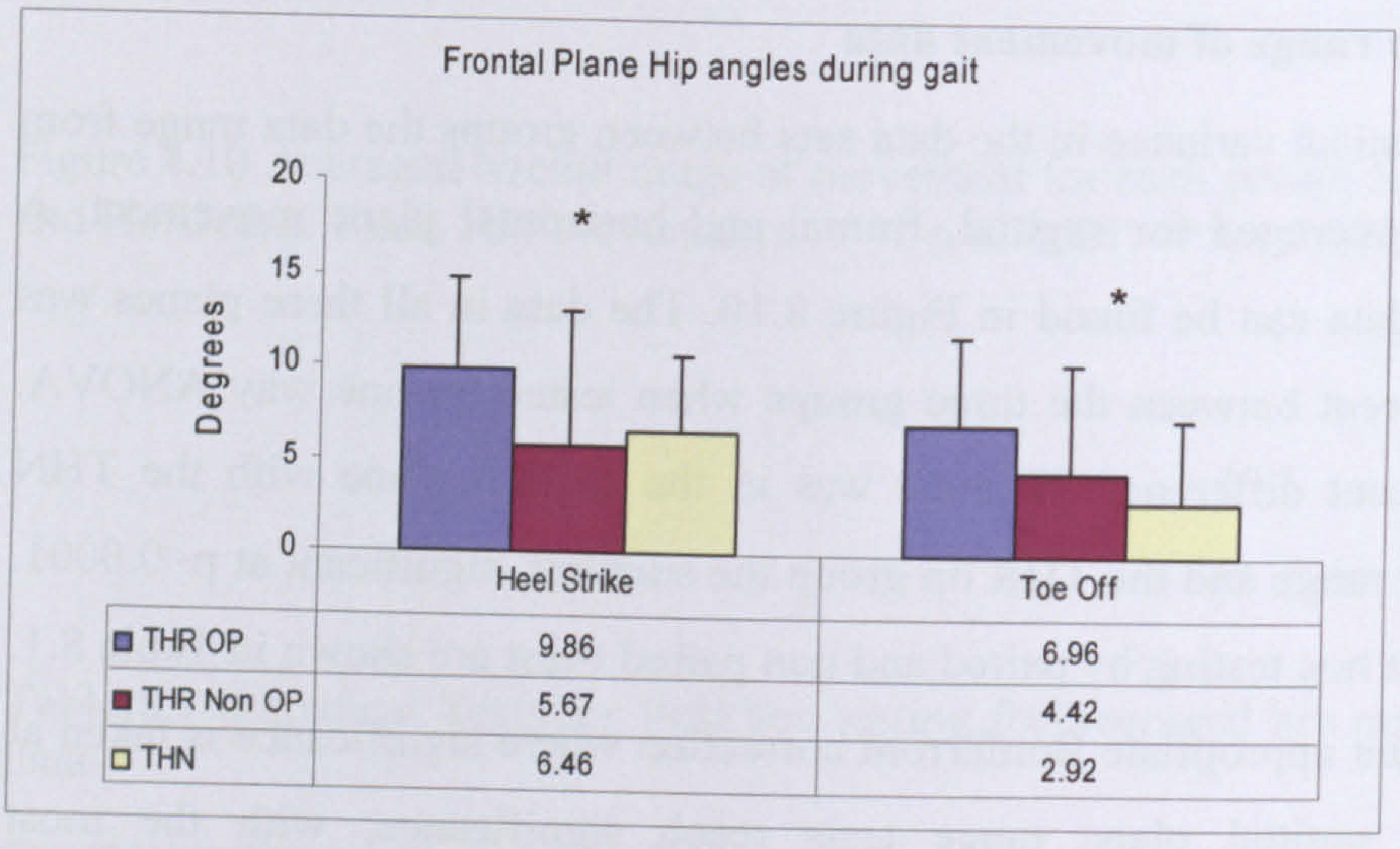
In both the frontal and the horizontal planes post hoc statistical testing showed no significant difference between the THR op and THR non op data (Table 8.1) but these sets of data were significantly different to that of the THN group.

Mean movement was also assessed by identifying mean data at two key points in the gait cycle; initial contact or heel strike and at the transition of stance to swing: toe off. Averaged hip data per group for the sagittal, frontal and horizontal planes are presented in Figure 8.11 – 8.13 (p172A). Data for horizontal plane movement was



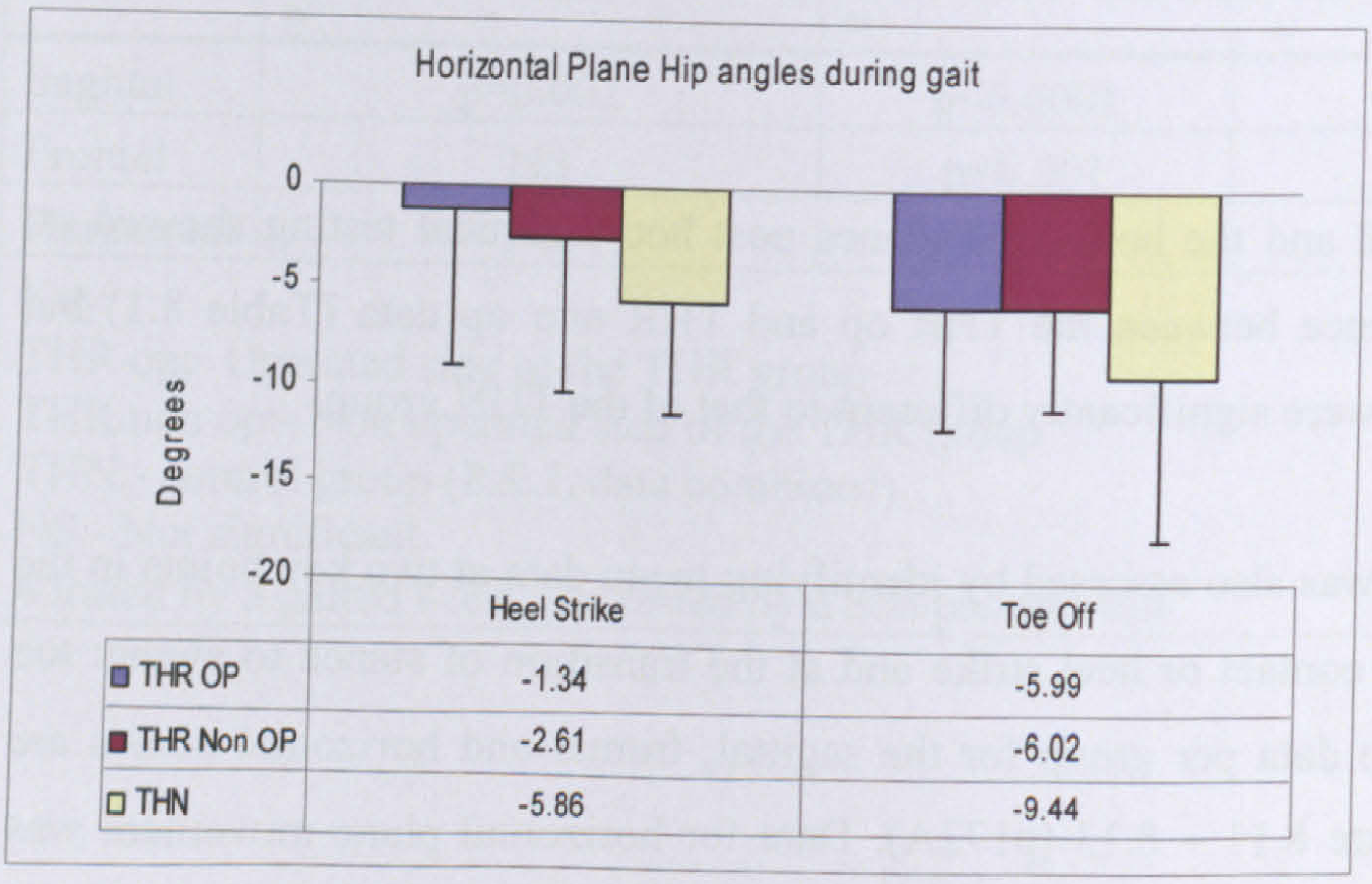
	Heel Strike	Toe Off
🟦 THR OP	25.45	9.56
🟥 THR Non OP	29.05	3.89
🟨 THN	29.95	-0.64

Figure 8.11 Averaged range of movement at Heel Strike and Toe Off for each group; sagittal plane hip movements, * p=0.04, **** p=0.001



	Heel Strike	Toe Off
🟦 THR OP	9.86	6.96
🟥 THR Non OP	5.67	4.42
🟨 THN	6.46	2.92

Figure 8.12 Averaged range of movement at Heel Strike and Toe Off for each group; frontal plane hip movements * p=0.03, 0.02



	Heel Strike	Toe Off
🟦 THR OP	-1.34	-5.99
🟥 THR Non OP	-2.61	-6.02
🟨 THN	-5.86	-9.44

Figure 8.13 Averaged range of movement at Heel Strike and Toe Off for each group; horizontal plane hip movements, no significant difference.

not significant (Figure 8.13) when tested by one way ANOVA indicating that there is no significant difference between the groups at either heel strike or toe off. It should be noted that the THN group had larger values than either of the other groups and that the THR op group had the least. The high standard deviations for all data sets demonstrate considerable variance within each of the groups.

Data for the sagittal and frontal planes showed significant differences at both heel strike and toe off with the largest difference at toe off in the sagittal plane (p=0.001). The standard deviations for all groups in the frontal plane (Figure 8.12) are large.

Results from post hoc paired and non paired t-test show that there is a significant difference between the operated side and the control group (THR op vs THN) in both the sagittal and frontal planes at both heel strike and toe off (Table 8.2).

Despite an overall significant difference in sagittal plane data at heel strike when tested by one way ANOVA post hoc testing with Bonferroni correction showed that significance was not reached for sagittal plane heel strike data. Significance was reached for sagittal plane toe off data between the THR op and non op data.

Table 8.2 Post hoc statistical testing of hip movement at Heel Strike and Toe Off

Plane		THR op vs THR non op ≈	THR op vs THN ≡	THR non op vs THN ≡
Sagittal	Heel Strike	NS	p=0.03	NS
	Toe Off	p=0.01	p<0.0001	NS
Frontal	Heel Strike	NS	p=0.01	NS
	Toe Off	NS	p=0.004	NS

Key:
THR op:- Operated side of the THR group
THR non op:- Non operated side of the THR group
THN:- control group (R& L data combined)
NS:- Not significant
≈ tested by a paired t-test, ≡ tested by a non paired t-test

8.2.5 Summary of hip results

Summary of hip results

- Significant differences in range of sagittal ($p<0.0001$), frontal ($p=0.0003$) and horizontal ($p=0.004$) plane hip movements were identified between the three groups using one-way analysis of variance.
- Post hoc statistical testing using t-tests found differences between all the groups in the sagittal plane (THR op vs THR non op, $p=0.002$) (THR op vs THN, $p<0.0001$) (THR non op vs THN, $p=0.008$).
- Statistical differences were found between the THR op and THN range of hip movements and between the THR non op and THN groups in both the frontal and horizontal planes (Table 8.1, $p=0.001$ – 0.037).
- Significant differences were identified at heel strike and toe off in the sagittal ($p=0.04$, $p=0.001$) and frontal ($p=0.03$, $p=0.02$) plane hip movement between the three groups. Horizontal plane data were not significantly different.
- Post hoc statistical testing found differences between the THR op side and THN data in the sagittal and frontal plane, although with Bonferroni correction sagittal plane heel strike data were not significant. Significant differences were also found between the THR sides for sagittal plane heel strike data.
- Observation of the movement cycle patterns (Figure 8.7 – 8.9) show clear differences between the groups in all three planes.

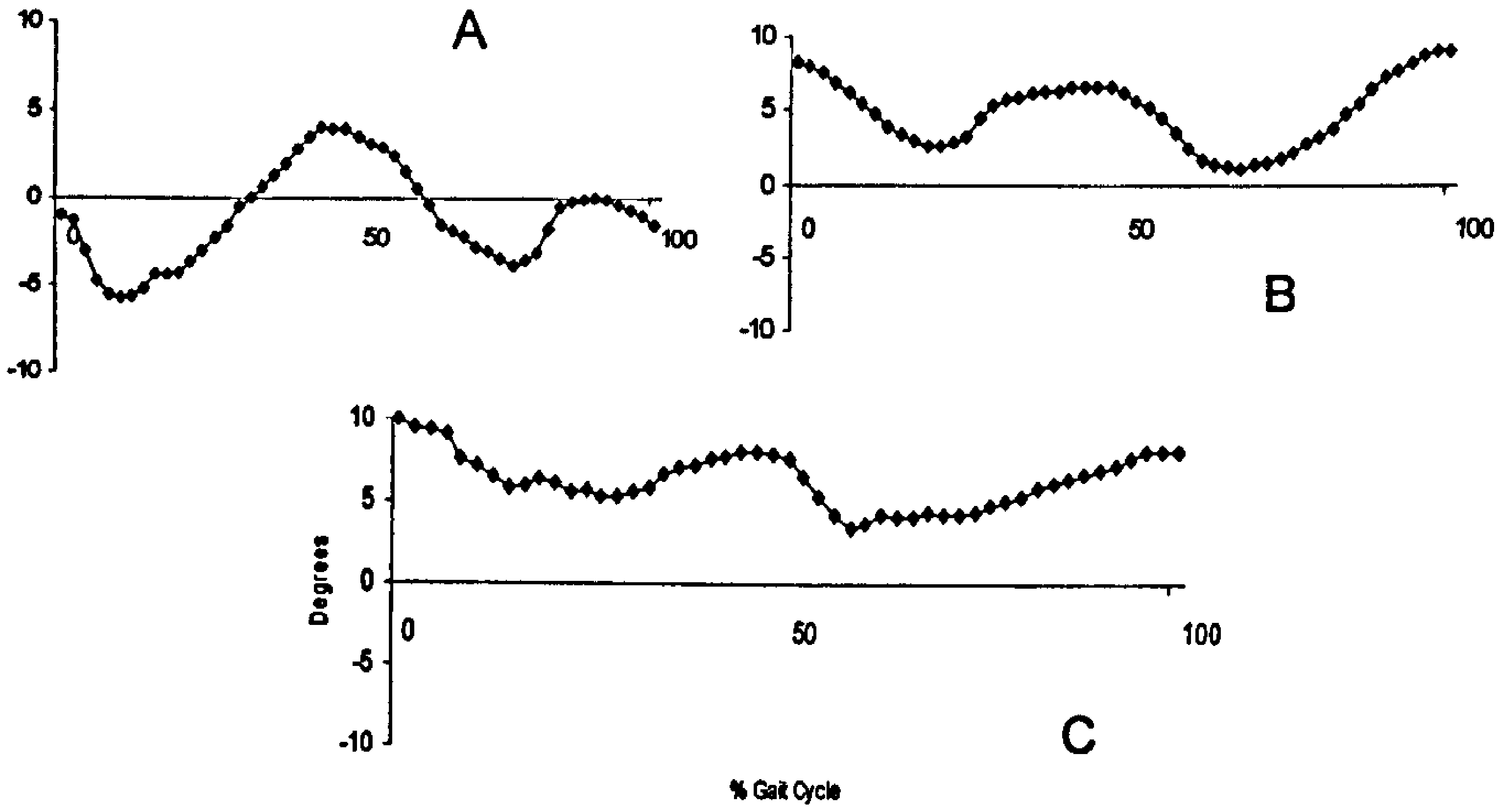


Figure 8.14
Sagittal Plane
Pelvic
Movements;
individual angle
time graphs, +ve
on y axis =
anterior tilt
A= THR OP
B = THR Non OP
C = THN

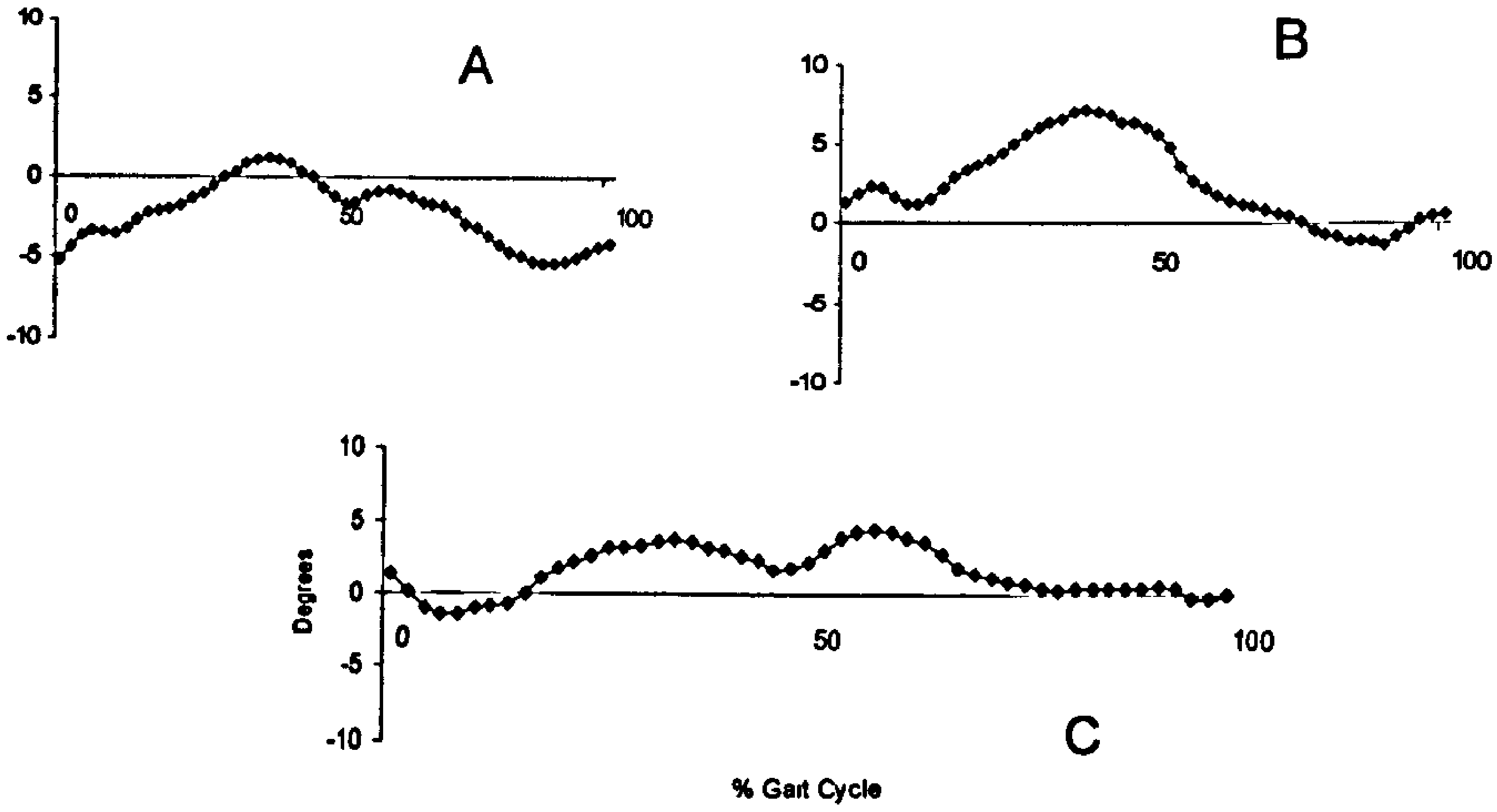


Figure 8.15 Frontal
Plane Pelvic
Movements,
individual angle time
graphs +ve on y
axis = tilt to same
(loaded/ weight
bearing) side
A= THR OP
B = THR Non OP
C = THN

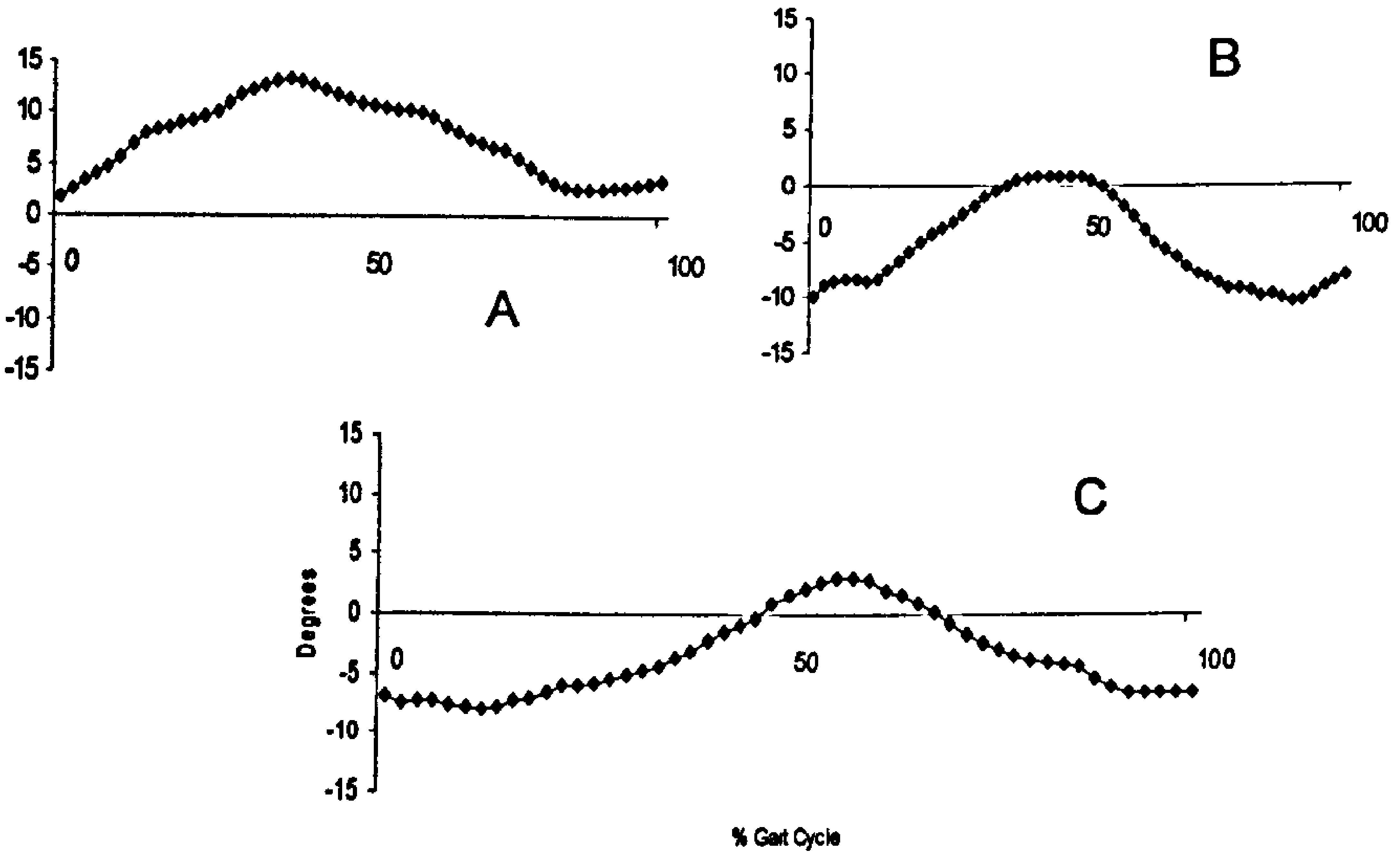


Figure 8.16 Horizontal
Plane Pelvic
Movements; individual
angle time graphs, +ve
on y axis = forward
rotation.
A= THR OP
B = THR Non OP
C = THN

Time is represented as 100% of the gait cycle is on the x (abscissa) axis and degrees of motion on the y (ordinate) axis for all three figures.

8.3 RANGE OF MOTION – PELVIS

For all pelvic movement graphs, the positive direction for the sagittal plane represents anterior tilt (pelvis moving forward and down), in the frontal plane; tilt to the measured side (pelvis titling to weight bearing side), and in the horizontal plane, forward rotation (pelvis rotates forward on the side being measured). Mean group data is presented in Appendix S. Tests for normal distribution and statistical analysis of the mean data is also presented in Appendix S. Description of axes and pelvis movement can be found in Figure 8.A, p175A.

8.3.1 Individual Pelvic Data Graph per group

Representative pelvic angle time graphs for each of the groups for sagittal, frontal and horizontal plane motion during gait are displayed in Figures 8.14 – 16. The graphs are displayed as described in section 8.1 and the axes values are the same for each of the groups per plane. The pelvis as a complete skeletal unit functions in opposing directions during motion of the right or left lower limbs during normal gait. To assess potential differences in the THR group pelvic measures were taken during footfalls of both operated and non operated limbs. Patterns of movement between the groups will be discussed when the averaged curves are presented in section 8.3.3.

8.3.2 Averaged pelvic angle time graph per individual

Examples of the averaged pelvic movements in each plane from one individual per group can be seen in Figures 8.17 – 8.19 (p175). Mean data is represented by the mid line in each graph with the lines on either side denoting one standard deviation.

Overall the averaged individual pelvic curves follow the mean data in section 8.3.3. Standard deviations varied within each of the groups with the THN group appearing to have the greatest variability. Presentation of mean data and standard deviations in section 8.3.4 will expand on these initial suggestions.

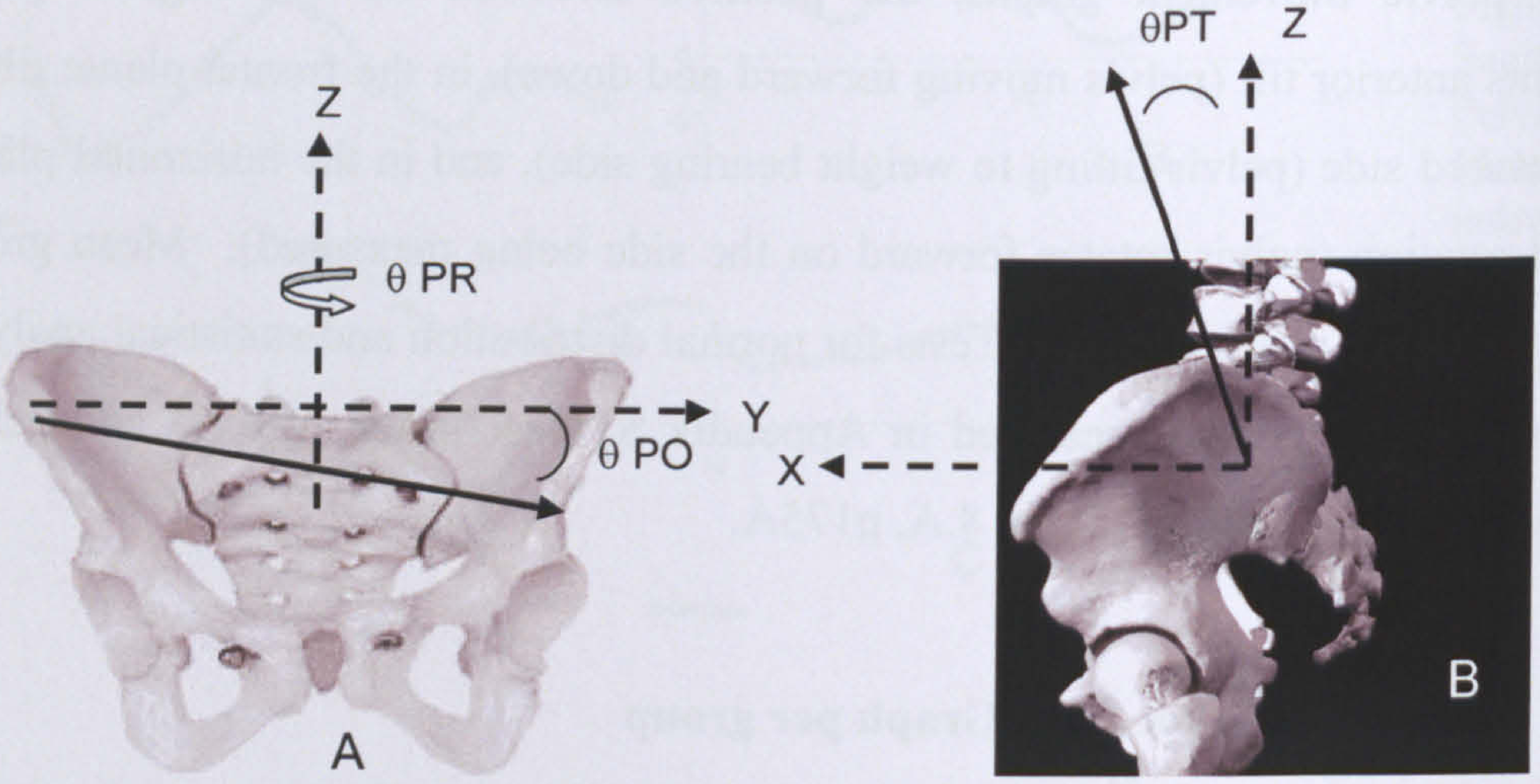


Figure 8.16A Pelvic angles under consideration
Motion of the pelvis was referred to a room-based co-ordinate system.

Figure A:
Pelvic Rotation (θPR) Horizontal plane movement;
Pelvic Obliquity (θPO) Frontal plane movement

Figure B:
Pelvic Tilt (θPT) Sagittal plane movement

(Pictures from Primal Pictures [site accessed 16.02.08]
https://auth.athensams.net/?ath_returl=%22http://www.anatomy.tv/%22&ath_dspid=PRIMAL.atv)

Description in Text	Plane	Pelvic movement (as above)	+ value on Figures 8.14 – 8.22
Anterior tilt	Sagittal	Pelvic Tilt	Both ASIS rotate down and forward
Tilt to same side	Frontal	Pelvic Obliquity	ASIS on weight bearing side dips
Forward rotation	Horizontal	Pelvic Rotation	ASIS on weight bearing side moves forward over the weight bearing foot

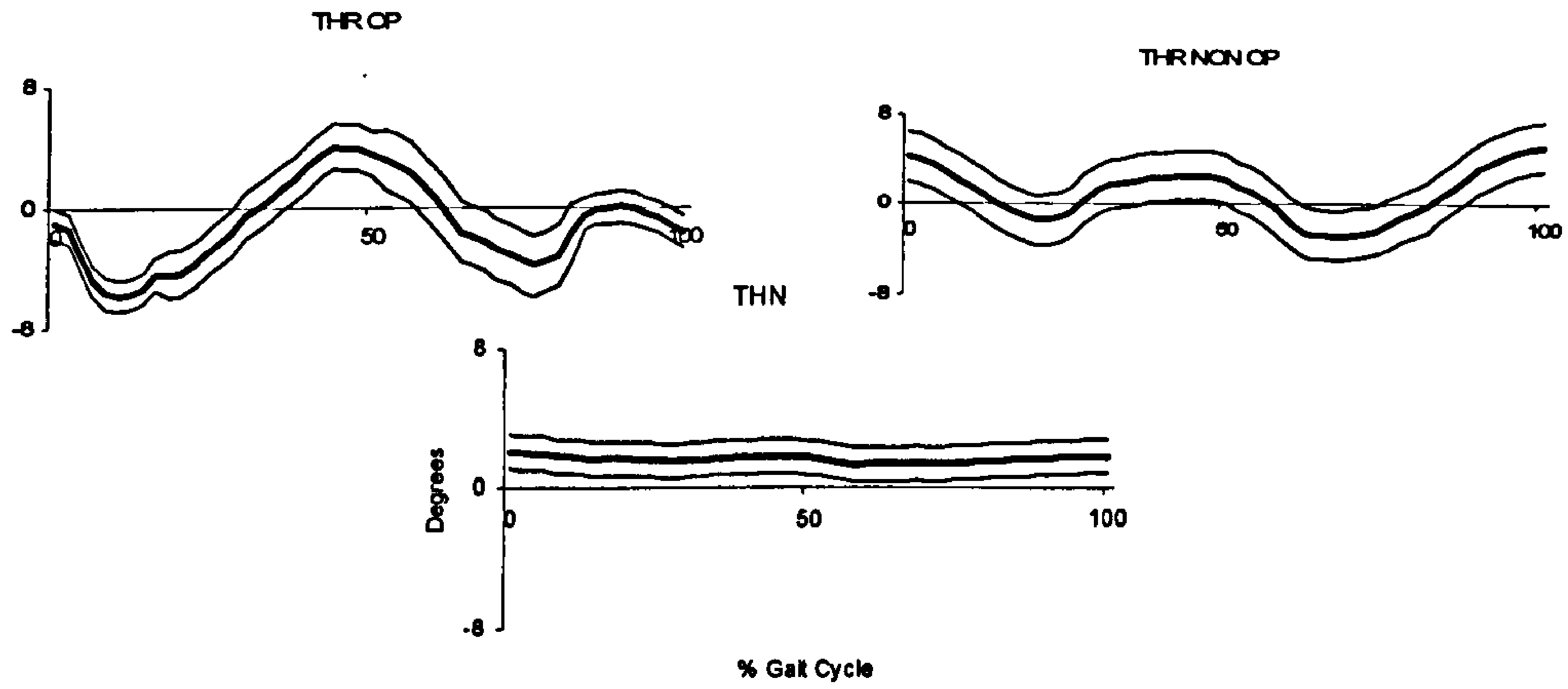


Figure 8.17 Sagittal Plane Pelvic Movements; average of three walking trials for one person with standard deviations, y axis Degrees of motion, +ve = anterior tilt, x axis % gait cycle

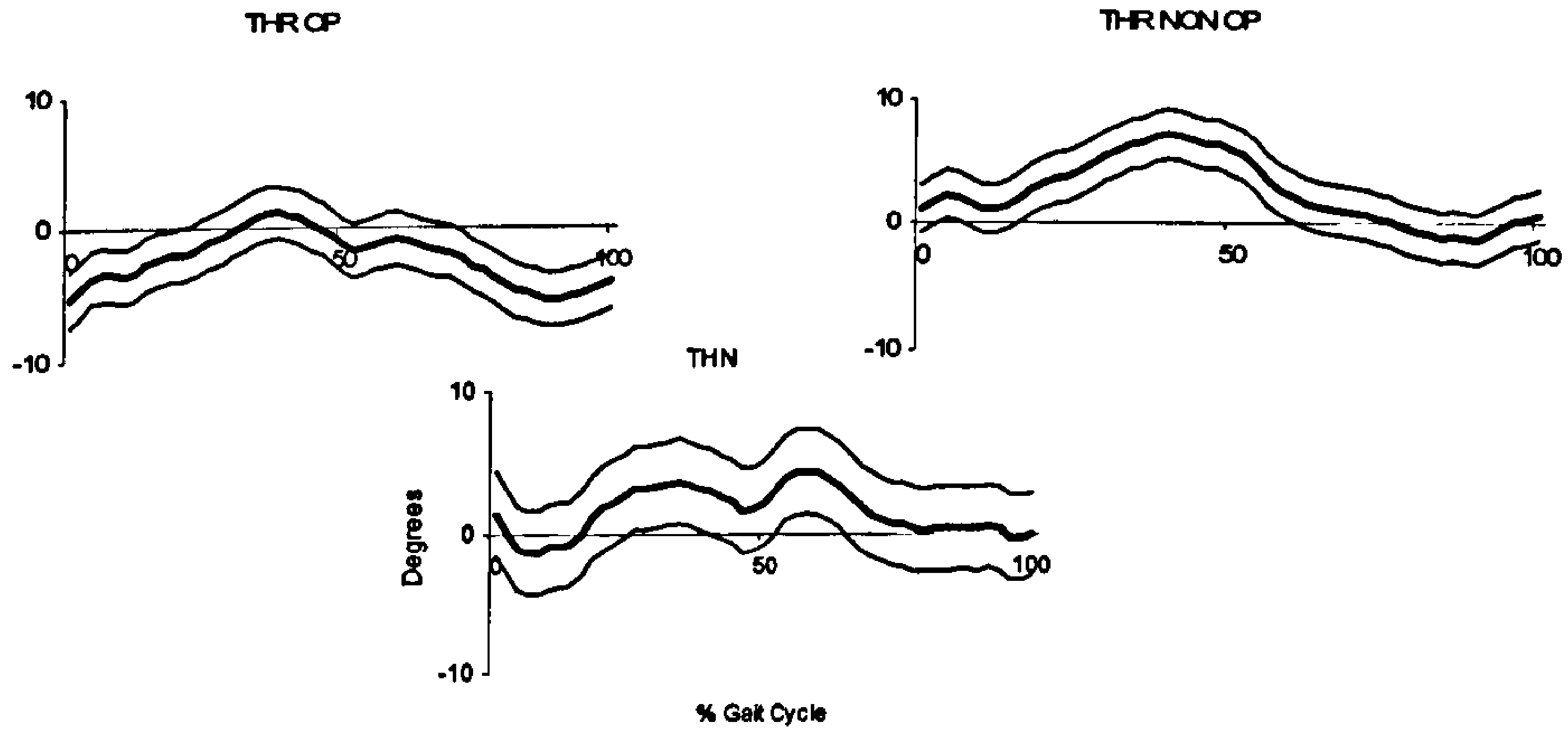


Figure 8.18 Frontal Plane Pelvic Movements; average of three walking trials for one person with standard deviations, y axis Degrees of motion, +ve = lateral tilt to weight bearing side, x axis % gait cycle

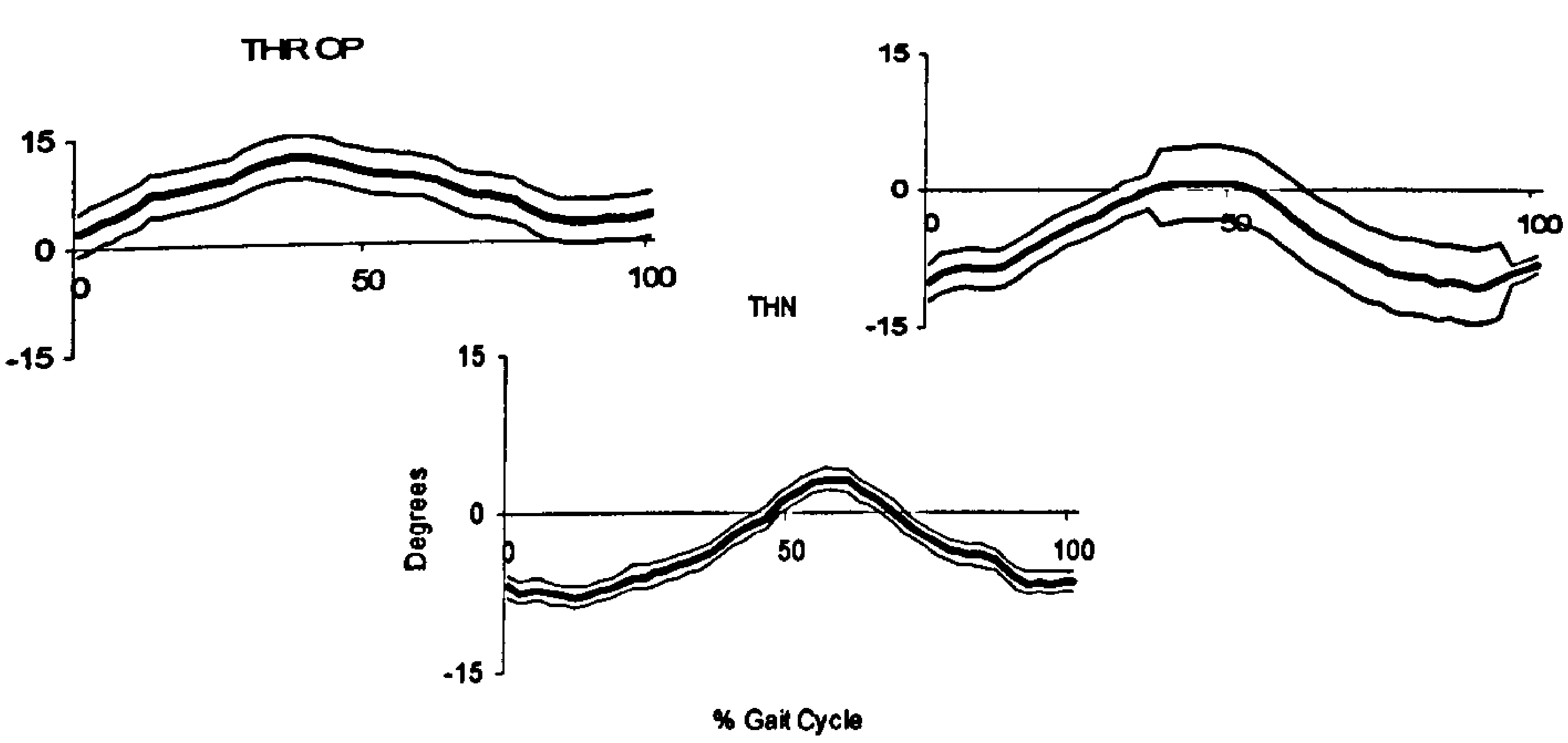


Figure 8.19 Horizontal Plane Pelvic Movements; average of three walking trials for one person with standard deviations, y axis Degrees of motion, +ve = rotation to same side, x axis % gait cycle

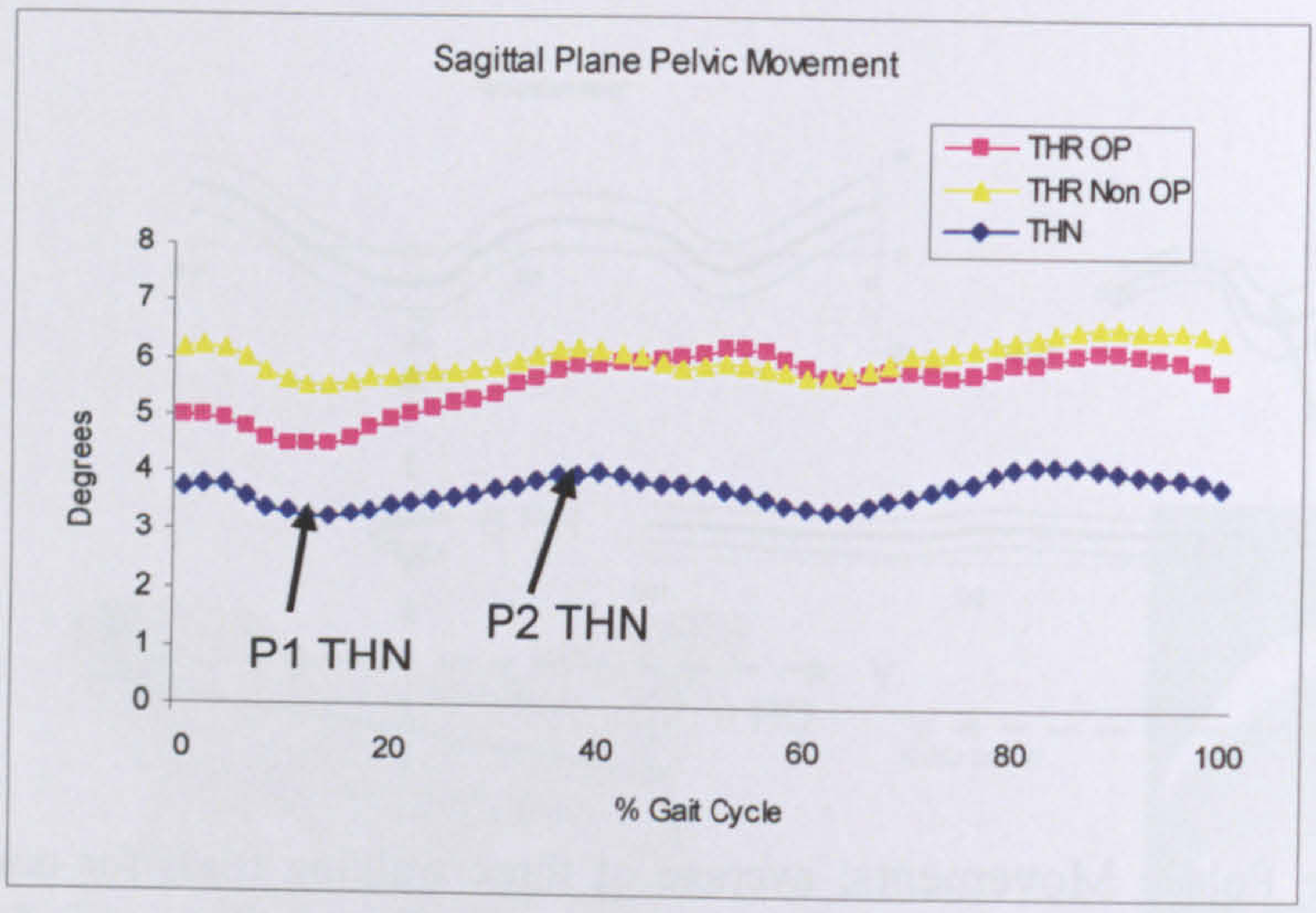


Figure 8.20
Sagittal Plane Pelvic movements; averaged graph for each group, +ve on y axis = anterior tilt

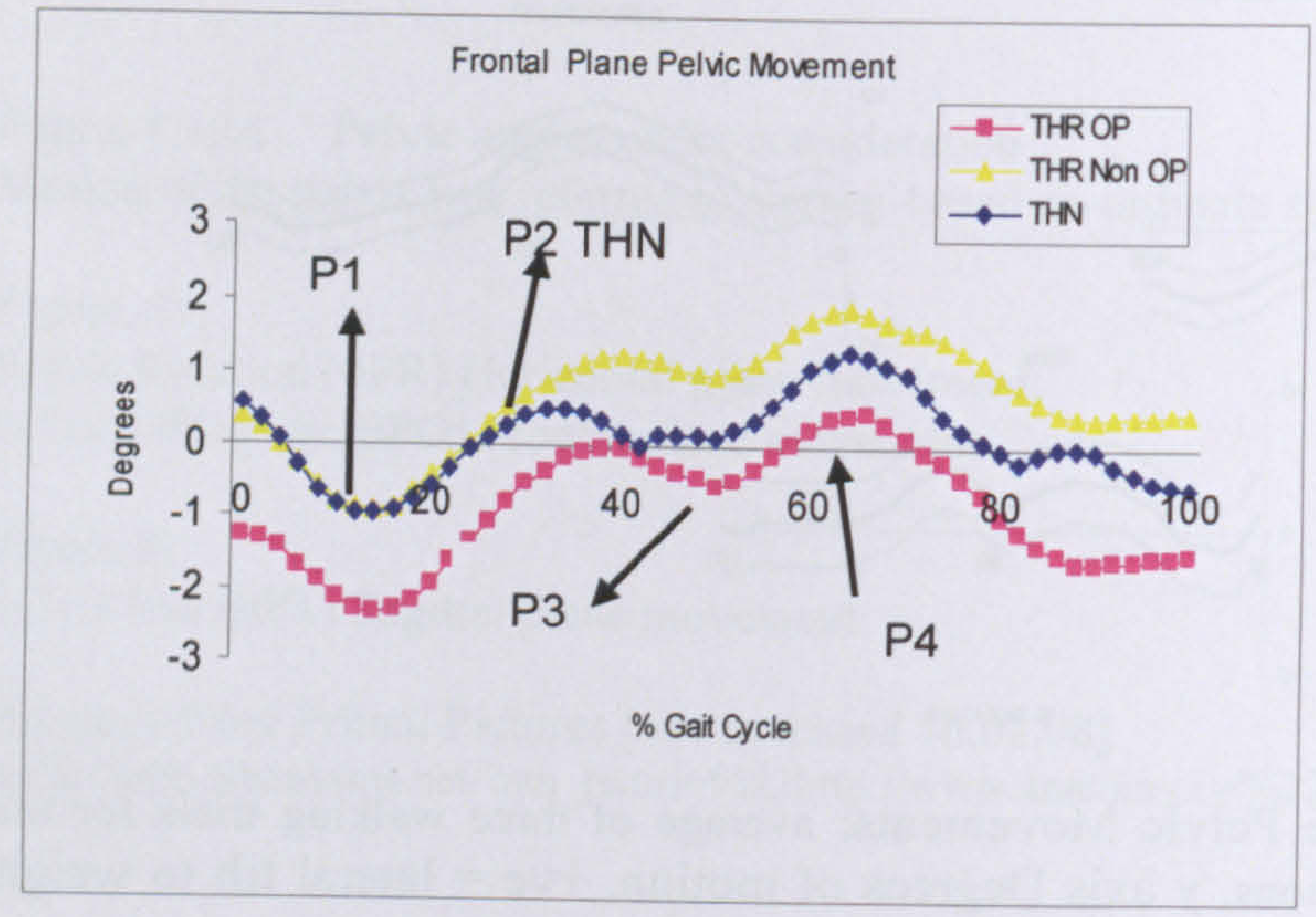


Figure 8.21
Frontal Plane Pelvic movements; averaged graph for each group, +ve on y axis = tilt to same (loaded/ weight bearing) side

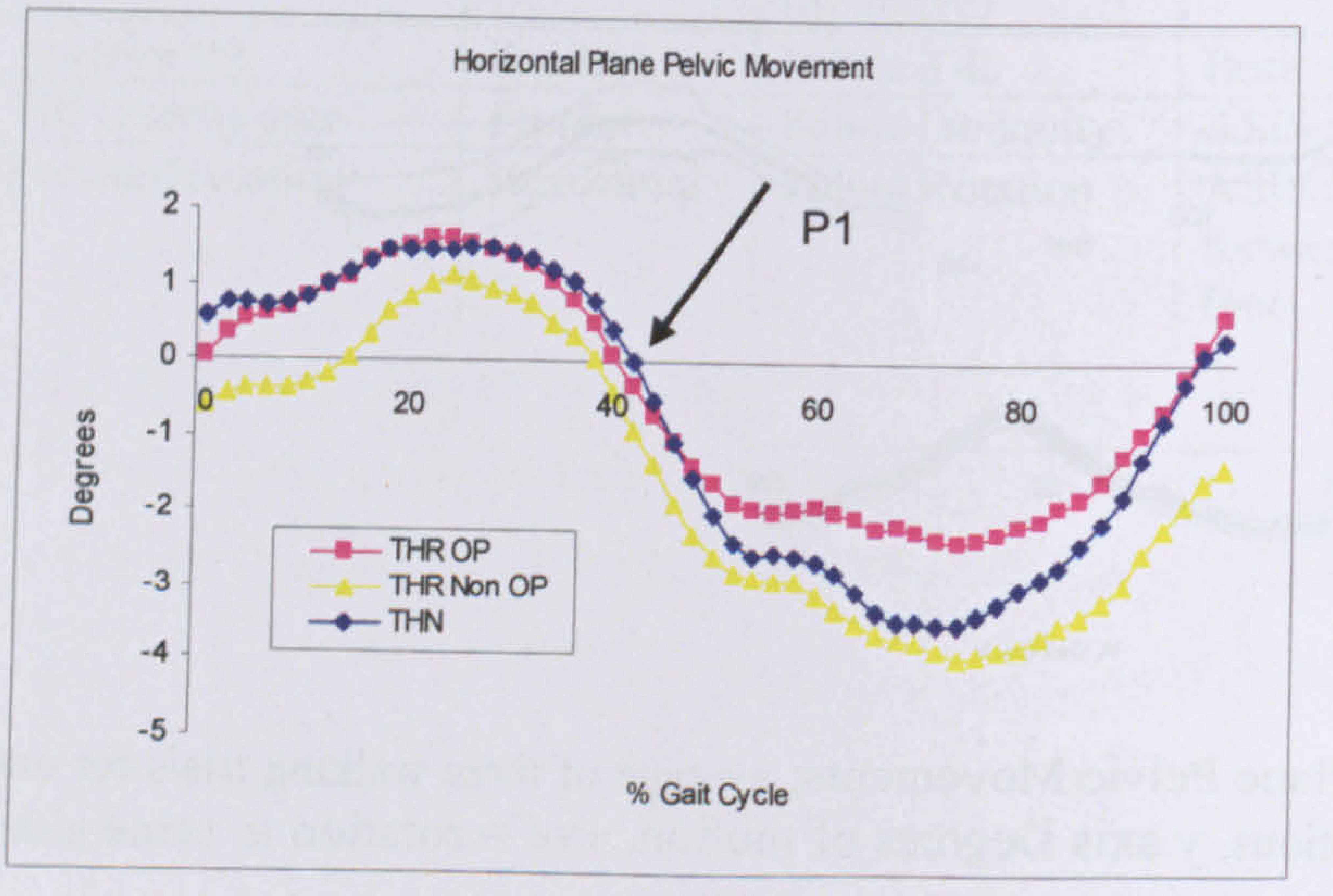


Figure 8.22 Horizontal Plane Pelvic movements; averaged graph for each group, +ve on y axis = forward rotation

8.3.3 Averaged pelvic data per group

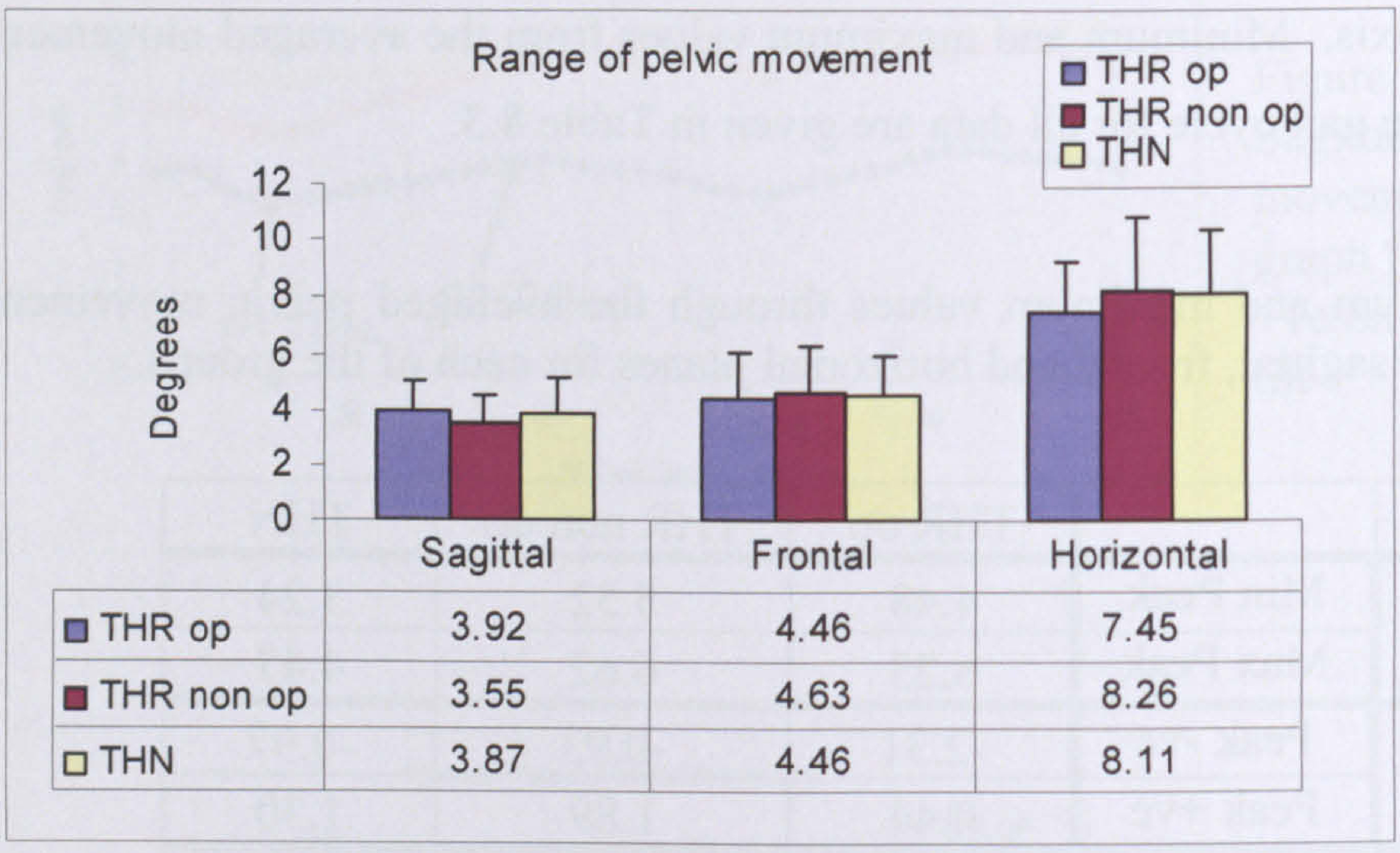
Averaged pelvic movements per group in each plane can be seen in Figures 8.20 – 8.22 with time represented as 100% of the gait cycle on the X axis and degrees of motion on the y axis. Minimum and maximum values from the averaged movement curves through the gait cycle for all data are given in Table 8.3.

Table 8.3 Minimum and maximum values through the averaged pelvic movement data curves in the sagittal, frontal and horizontal planes for each of the groups.

		THR op	THR non op	THN
Sagittal	Min Peak	4.48	5.52	3.24
	Max Peak	6.23	6.62	4.47
Frontal	Peak -ve	-2.31	-0.93	-0.97
	Peak +ve	0.44	1.89	1.30
Horizontal	Peak -ve	-2.41	-3.95	-3.49
	Peak +ve	1.62	1.14	1.53
All data measured in Degrees				

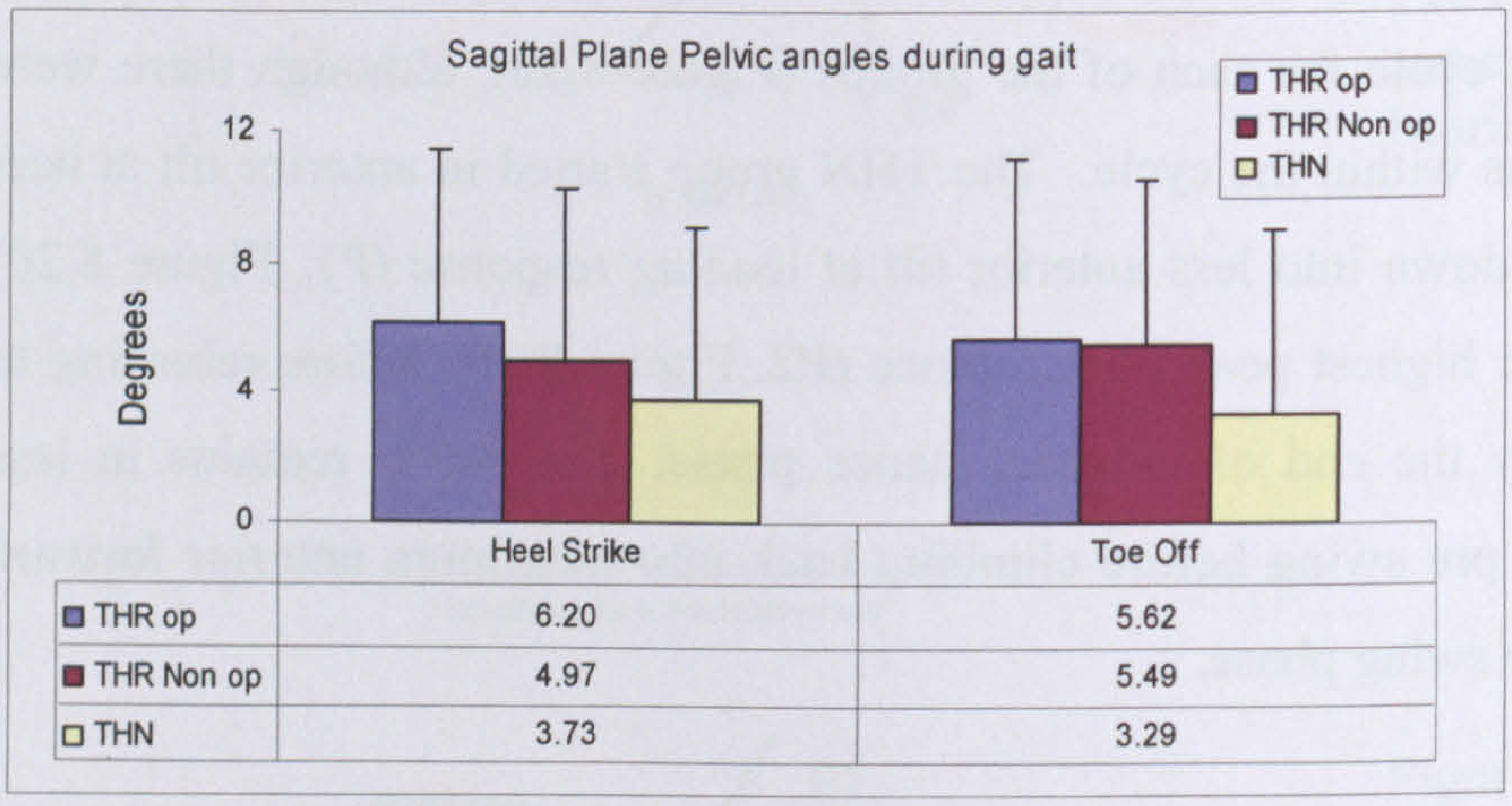
Sagittal plane movements remained in an anterior tilt position (positive angle) throughout the gait cycle for each of the groups (Figure 8.20), although there were two distinct patterns within the cycle. The THN group started in anterior tilt at heel strike then dipped down into less anterior tilt at loading response (P1, Figure 8.20) then climbed to the highest peak at midstance (P2, Figure 8.20) before returning to less anterior tilt by the end of terminal stance phase. The pelvis remains in less anterior tilt during pre swing before climbing back into maximum anterior forward tilt at the end of the swing phase.

The THR non op group followed the same pattern but the variance between the highest and lowest anterior tilt is smaller than the THN group. The changes in anterior tilt for both the THR op and THR non op were small but overall both of these groups lie in more anterior tilt throughout the gait cycle than the THR group. The average curve for the THR op group starts off in a similar pattern to both the THR non op and THR groups from heel strike through mid stance but continues to



	Sagittal	Frontal	Horizontal
THR op	3.92	4.46	7.45
THR non op	3.55	4.63	8.26
THN	3.87	4.46	8.11

Figure 8.23 Averaged overall range of movement for each group; sagittal, frontal and horizontal plane pelvic movements, no significant difference



	Heel Strike	Toe Off
THR op	6.20	5.62
THR Non op	4.97	5.49
THN	3.73	3.29

Figure 8.24 Averaged range of movement at Heel Strike and Toe off for each group; sagittal plane pelvic movements, no significant difference

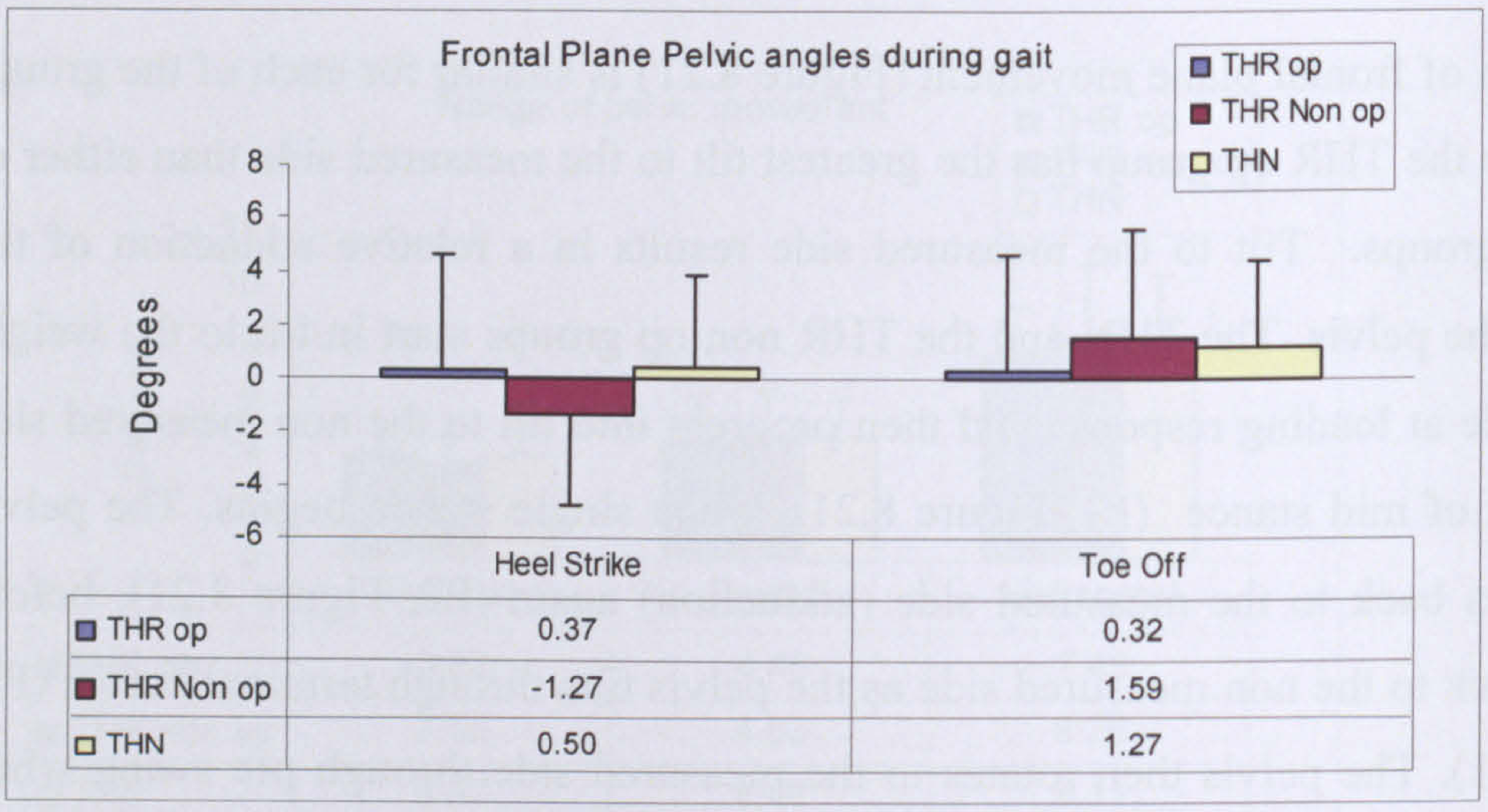
increase slowly to the start of terminal stance. Then anterior tilt reduces slightly before increasing through the swing phase.

The pattern of frontal plane movement (Figure 8.21) is similar for each of the groups but that for the THR op group has the greatest tilt to the measured side than either of the other groups. Tilt to the measured side results in a relative adduction of the femur on the pelvis. The THN and the THR non op groups start in tilt to the weight bearing side at loading response and then progress into tilt to the non measured side at the start of mid stance (P1, Figure 8.21), when single stance begins. The pelvis then rotates back to the measured side (adduction) again (P2, Figure 8.21), before moving back to the non measured side as the pelvis tilts through terminal stance (P3, Figure 8.21). The pelvis then rotates to the measured side through pre swing when the opposite limb is measured. Through the swing phase the pelvis remains in neutral before returning to a slight tilt to the non measured side. The curve of the THR non op group follows this pattern but remains tilted to the non measured side through most of the stance phase, until the start of terminal stance when the pelvis moves back to the measured side (P4, Figure 8.21). From this point the pelvis returns titled to the non measured through the swing phase.

Movement in the horizontal plane (Figure 8.22) follows the same pattern for each of the groups with the THR non op group having less forward and more backward rotation than either of the other groups. The THR op group has less backward rotation than either the THR non op or THR groups. Rotation moves from forward to backwards at a similar point for each of the groups at approximately 42% of the gait cycle (P1, Figure 8.22, mid stance).

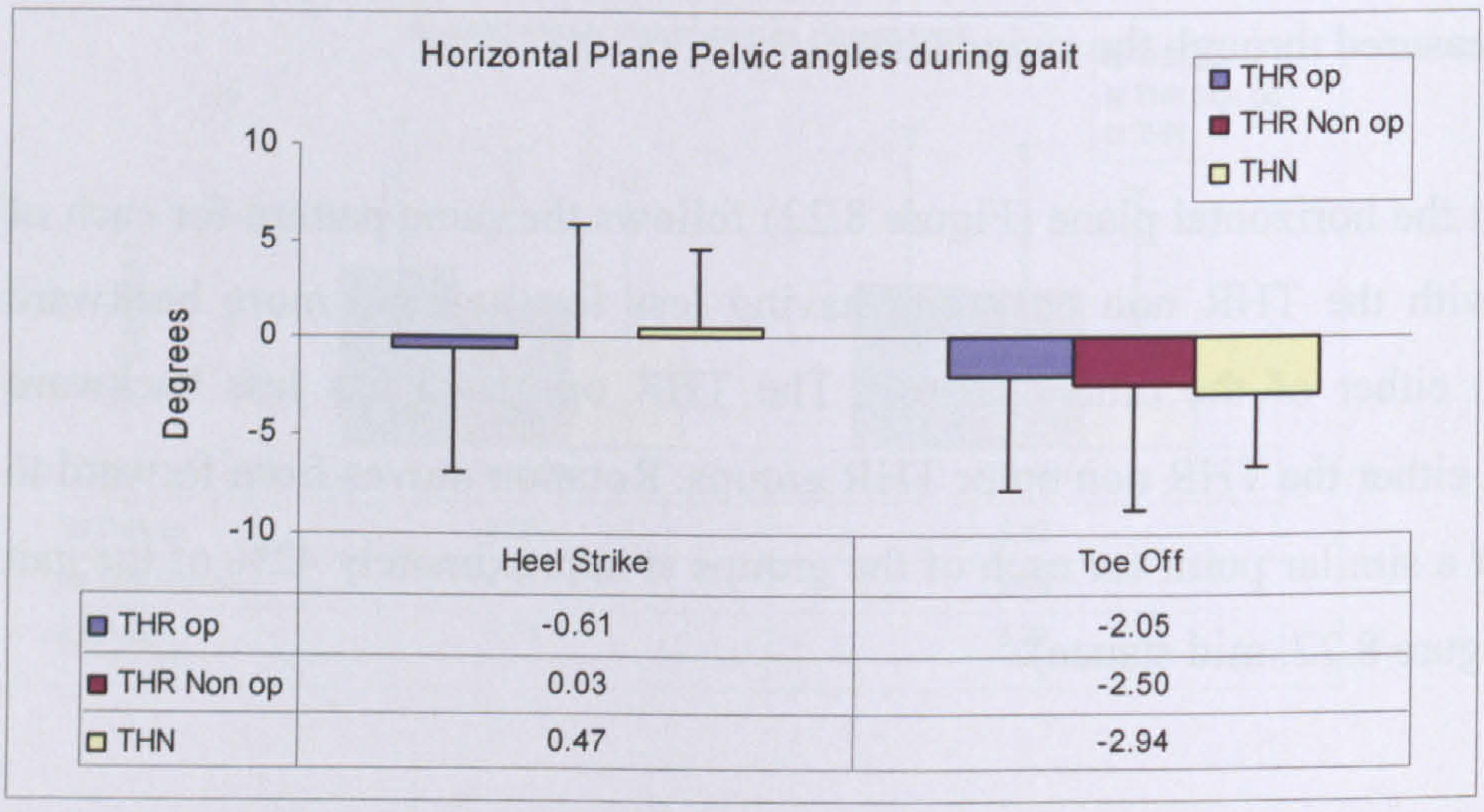
8.3.4 Mean pelvic range of movement data

Averaged pelvic movements per group in each plane can be seen in Figures 8.23 – 8.26 with time represented as 100% of the gait cycle on the x axis and degrees of motion on the y axis. Figure 8.23 represents the mean averaged range of movement in each of the sagittal, frontal and horizontal planes for each of the three groups. There was no significant difference between the groups in each of the planes when



	Heel Strike	Toe Off
THR op	0.37	0.32
THR Non op	-1.27	1.59
THN	0.50	1.27

Figure 8.25 Averaged range of movement at Heel Strike and Toe off for each group; frontal plane pelvic movements, no significant difference



	Heel Strike	Toe Off
THR op	-0.61	-2.05
THR Non op	0.03	-2.50
THN	0.47	-2.94

Figure 8.26 Averaged range of movement at Heel Strike and Toe off for each group; horizontal plane pelvic movements, no significant difference

tested by one way ANOVA. In the sagittal plane the THR op group had slightly more range than the other groups but this was the reverse in the horizontal plane, and all three groups demonstrated equal values in the frontal plane.

Figures 8.24 – 8.26 (Figure 8.24, p177A) show the averages data per group for the key gait events of Heel Strike, and Toe off. There was no statistical difference for either heel strike or toe off ranges in any of the planes of pelvic movement. The standard deviations for each of the groups in each of the planes are large, demonstrating a large variance of pelvic movement between the participants. The THR non op and THN group averages in the sagittal plane (Figure 8.24) were less than those for the THR op group for both heel strike and toe off. The THR op group had the largest range; 6.2° at heel strike and 5.62° at toe off with the THN group having the smallest 3.73° at heel strike and 3.29°at toe off.

In the frontal plane (Figure 8.25) the THR non op group had an average tilted position to the non measured side at heel strike where the other groups demonstrated a tilt to the measured side. By toe off all participants in the groups showed a tilt to the measured side, but the range was below two degrees for each of the groups. The mean range of rotation in the horizontal plane (Figure 8.26) was less than one degree at heel strike for each of the groups with the THR op group being in slight backward rotation whilst the others were in slight forward rotation. Again the standard deviations are large for both heel strike and toe off. By toe off all three groups demonstrate a backward rotation with less than one degree of difference between the three groups. The measures at heel strike are small and these fall below the reliability of the system and operator to measure motion, however these measures are averages for the group and the range presented is far greater denoted by the standard deviation bars.

8.3.5 Summary of pelvic movement results

Summary of pelvic movement results

- No significant difference was found in the range of sagittal, frontal and horizontal plane pelvic movement between the three groups, or at heel strike and toe off in the sagittal, frontal and horizontal plane pelvic movements between the three groups.
- Observation of the curve patterns (Figures 8.20 – 8.22) show that the THR op group has an altered pattern to the THN group in all three planes of movement. The THR non op group are in more anterior tilt than the THN group and have less frontal plane movement. In the horizontal plane less rotation is found at the start of the stance phase but this changes to an increased in backward rotation at the end of stance and the swing phase.

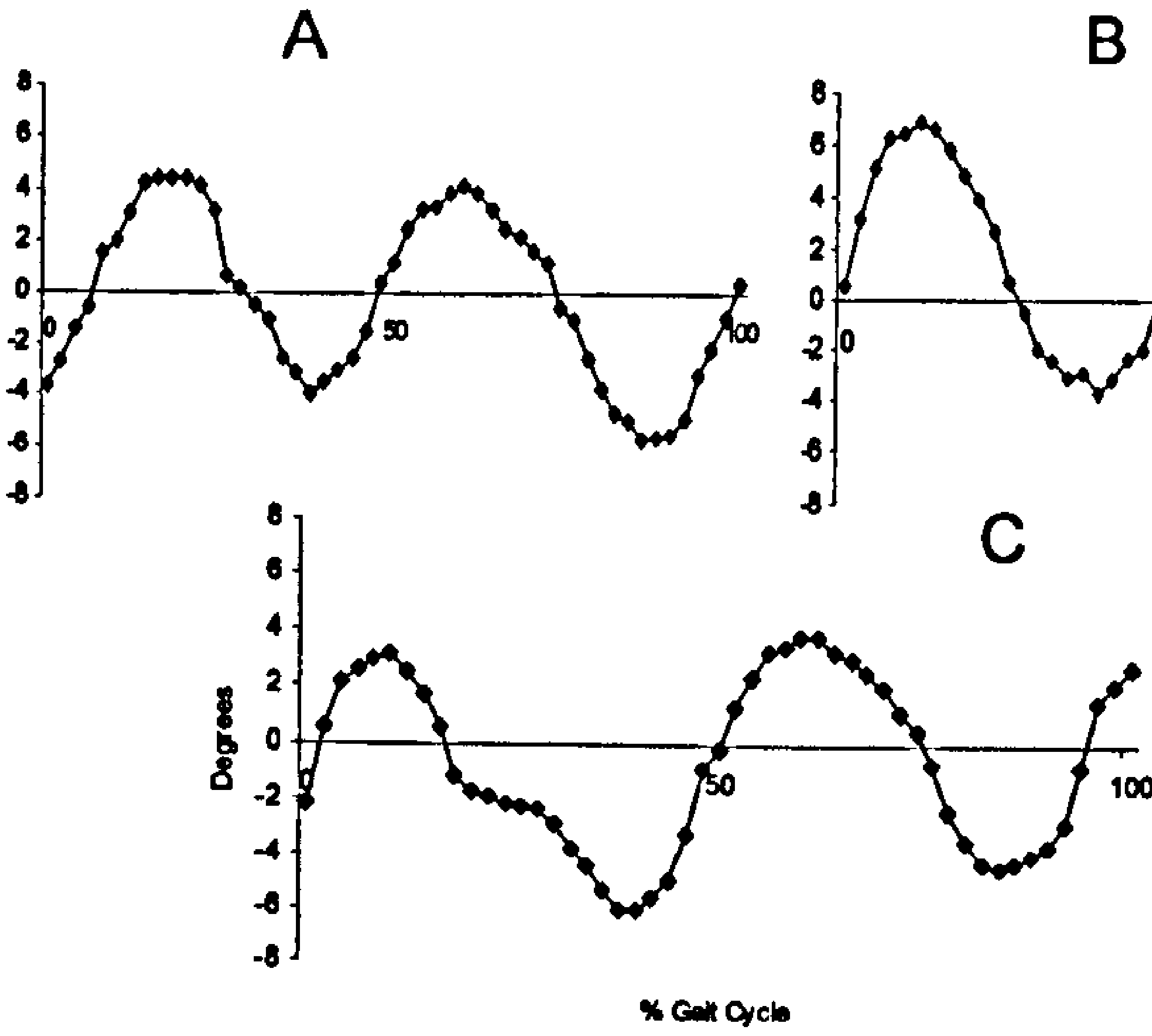


Figure 8.27 Sagittal Plane Lumbar Spine Movements; individual angle time graphs, +ve on y axis = forward flexion
A= THR OP
B = THR Non OP
C = THN

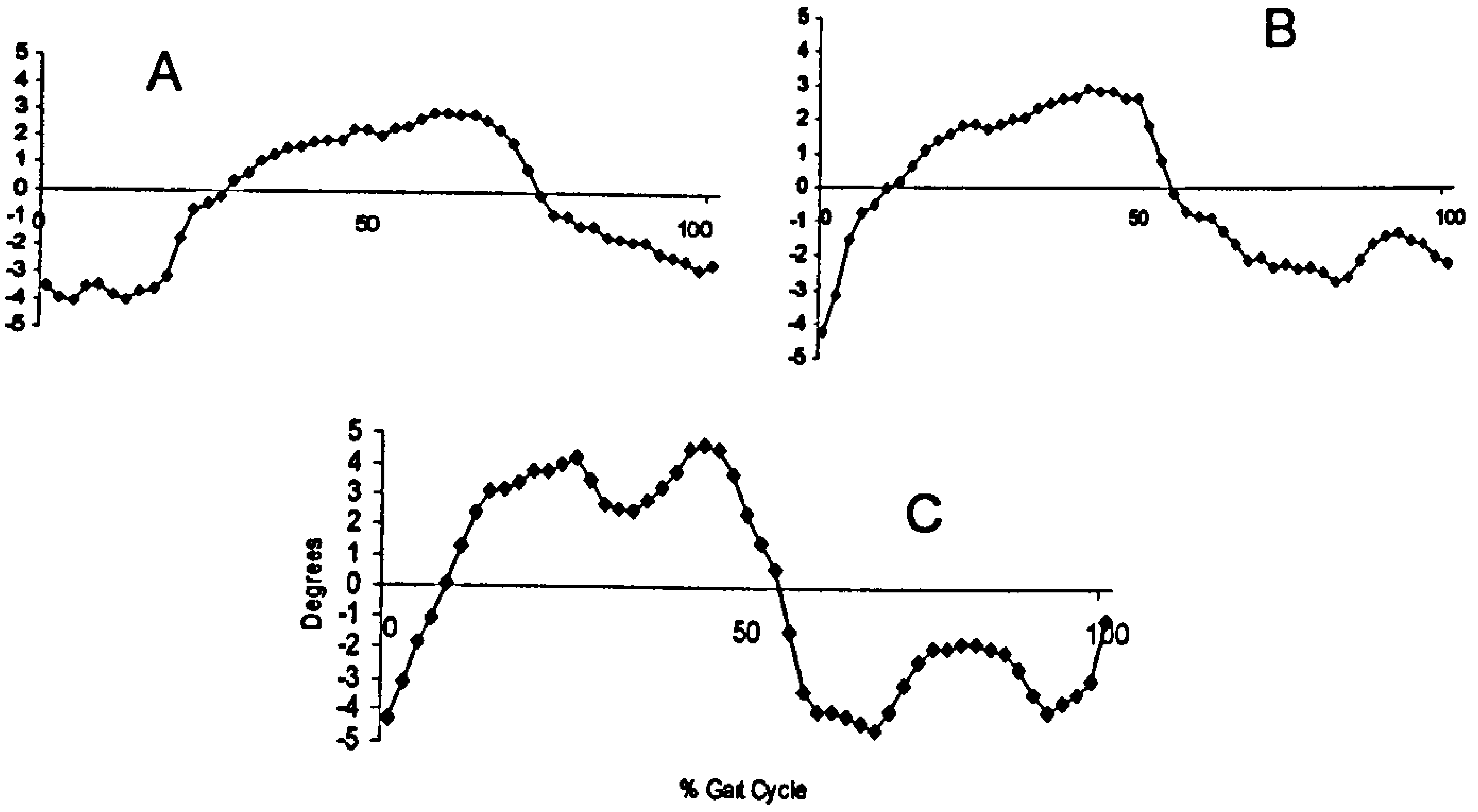


Figure 8.28 Frontal Plane Lumbar Spine Movements; individual angle time graphs, +ve on y axis = flexion to same/ weight bearing side
A= THR OP
B = THR Non OP
C = THN

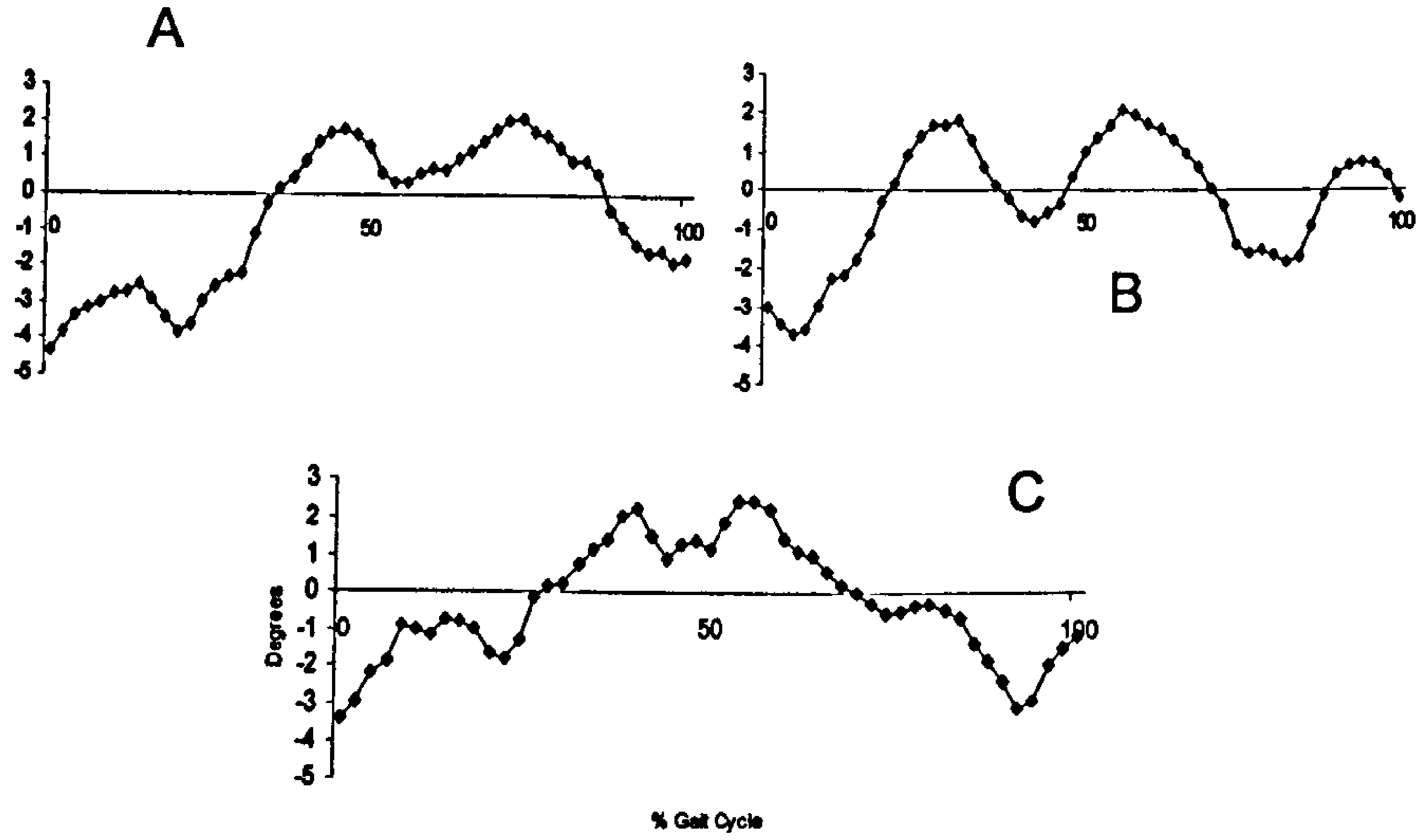


Figure 8.29 Horizontal Plane Lumbar Spine Movements; individual angle time graphs, +ve on y axis = rotation to same side
A= THR OP
B = THR Non OP
C = THN

Time is represented as 100% of the gait cycle is on the x (abscissa) axis and degrees of motion on the y (ordinate) axis for all three figures.

8.4 RANGE OF MOTION – LUMBAR SPINE

For all lumbar spine movement graphs, the positive direction for the sagittal plane represents flexion, in the frontal plane; side flexion to the side being measured, and in the horizontal plane, rotation to the same side (forward rotation). Mean group data is presented in Appendix T. Tests for normal distribution and statistical analysis of the mean data is also presented in Appendix T.

8.4.1 Individual lumbar spine data graph per group

Representative angle time graphs for each of the groups are displayed in Figures 8.27 – 29. Examples of lumbar spine movement curve from one individual from each of the groups during gait for each lumbar spine movement in each plane: sagittal, frontal and horizontal. These individuals are representative of the group. The graphs are displayed as described in section 8.1 and the axes values are the same for each of the groups per plane.

There was no difference between left and right values for the THN group, so data from the right and leg footfalls are considered together (Appendix T).

8.4.2 Averaged lumbar spine angle time graph per individual

Examples of the averaged lumbar spine movements in each plane from one individual per plane per group can be seen in Figures 8.30 -8.32 (p181). Mean data is represented by the mid line in each graph with the lies on either side denoting one standard deviation.

Sagittal plane movements had the greatest observed variation between individuals and the largest standard deviations of the three planes. To represent this, the graphs presented here (Figure 8.30, p181)) characterise the extreme of variance away from the norm as seen in the averaged graphs of three walking trails with standard deviations Figure 8.33 (p182A).

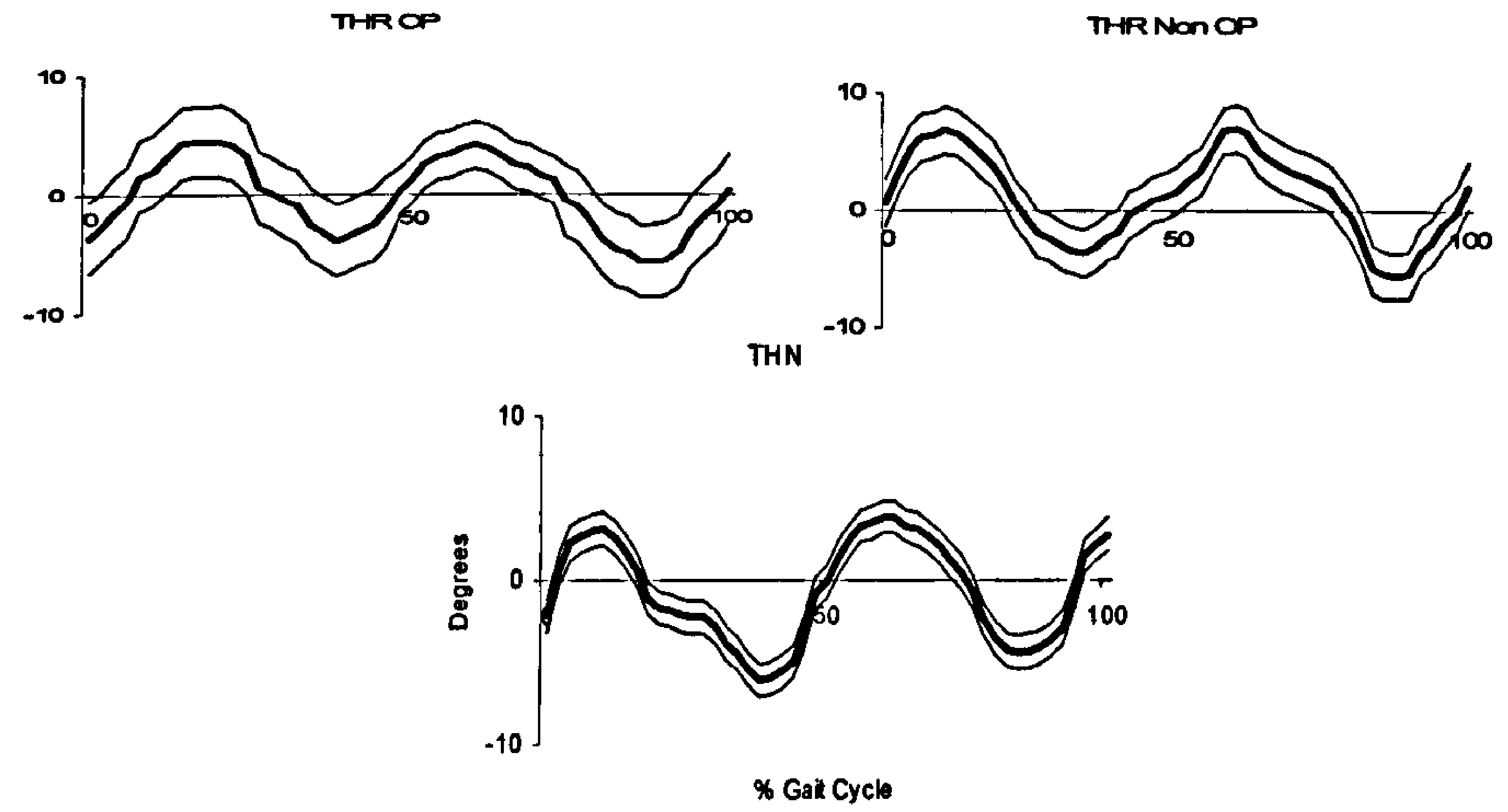


Figure 8.30 Sagittal plane lumbar spine movements; mean of three walking trials for one person with standard deviations. Degrees of motion y axis, +ve = flexion, % gait cycle x axis

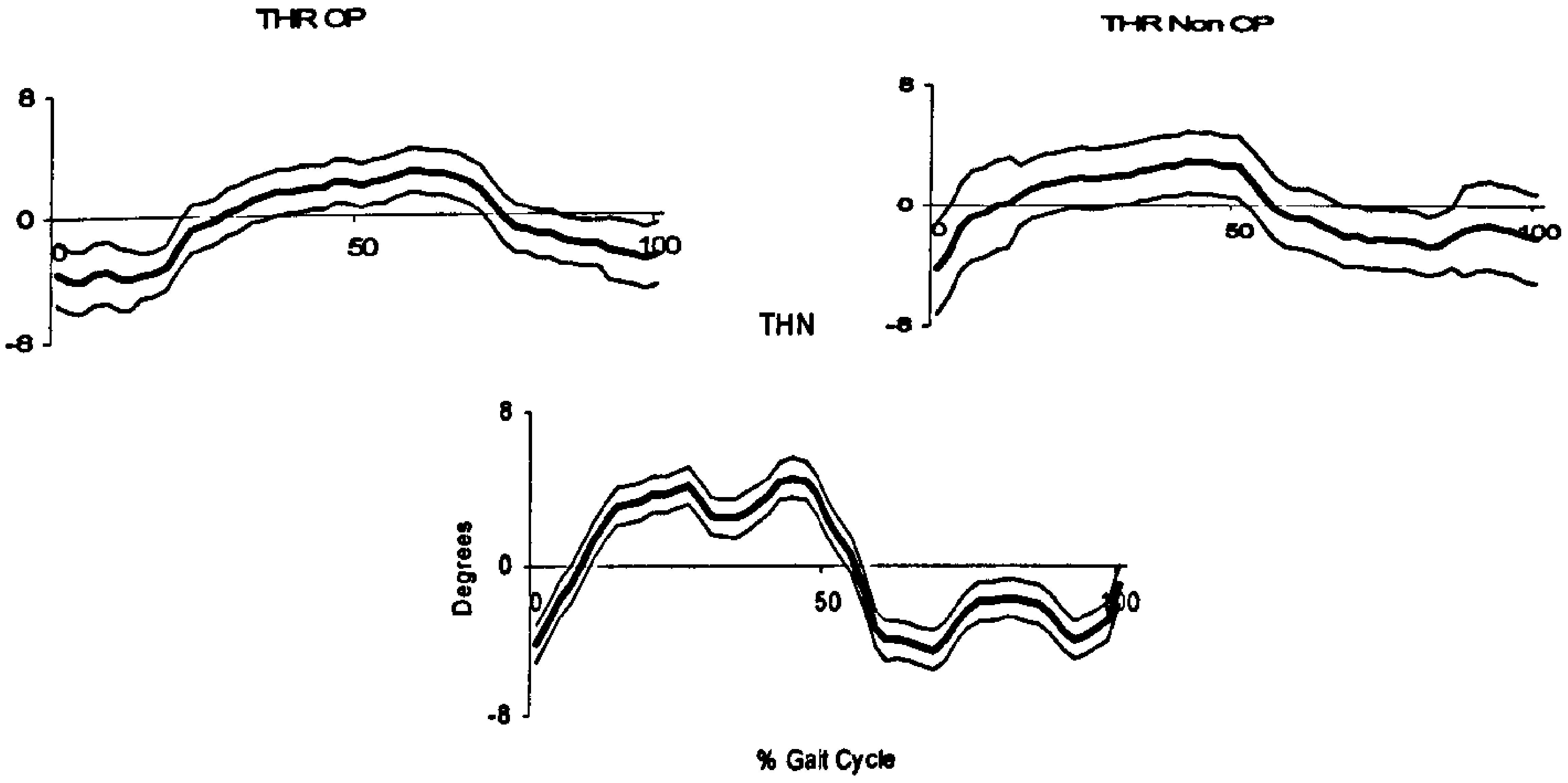


Figure 8.31 Frontal plane lumbar spine movements; mean of three walking trials for one person with standard deviations. Degrees of motion y axis, +ve = lateral flexion to weight bearing side, % gait cycle x axis

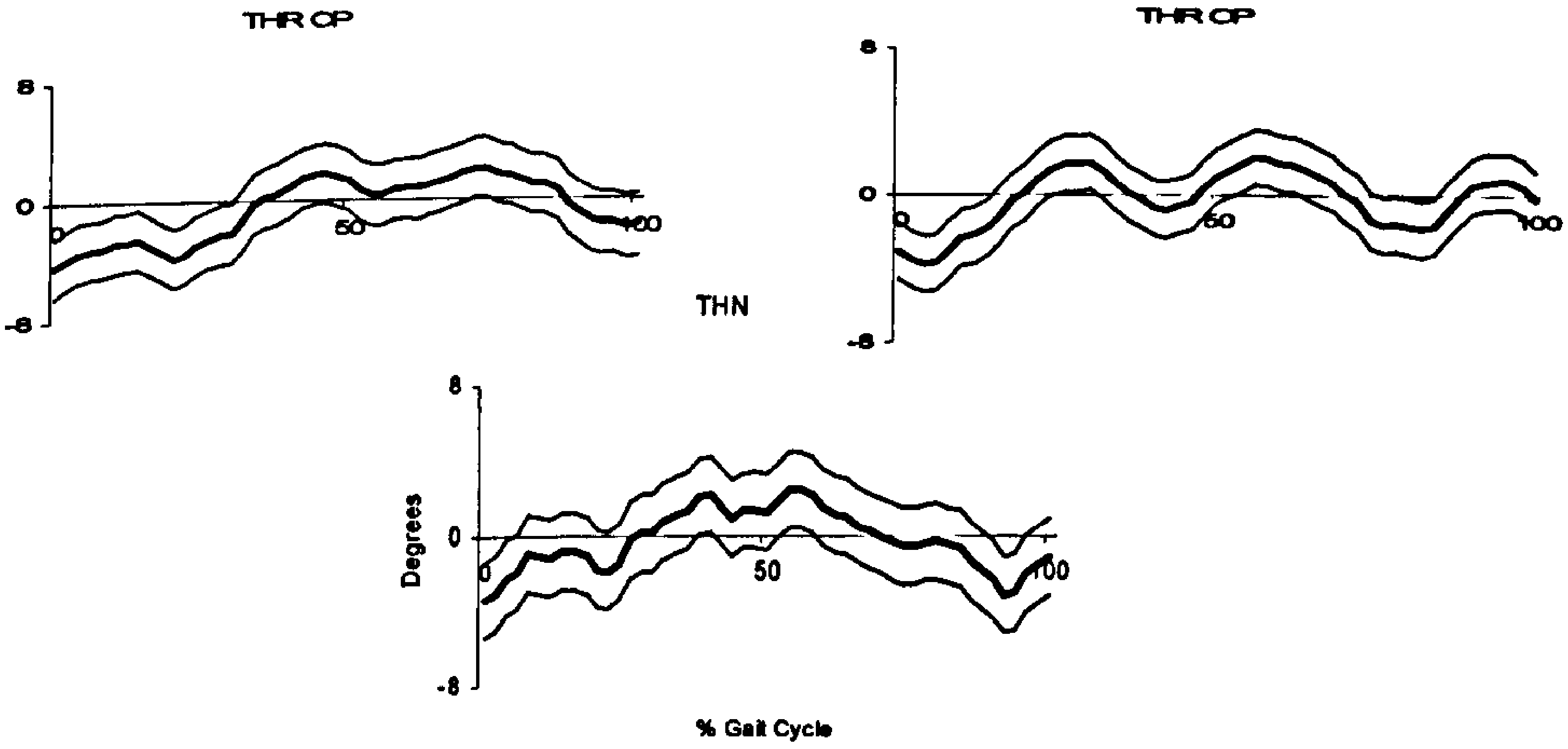


Figure 8.32 Horizontal plane lumbar spine movements; mean of three walking trials for one person with standard deviations Degrees of motion y axis, +ve = rotation to same side, % gait cycle x axis

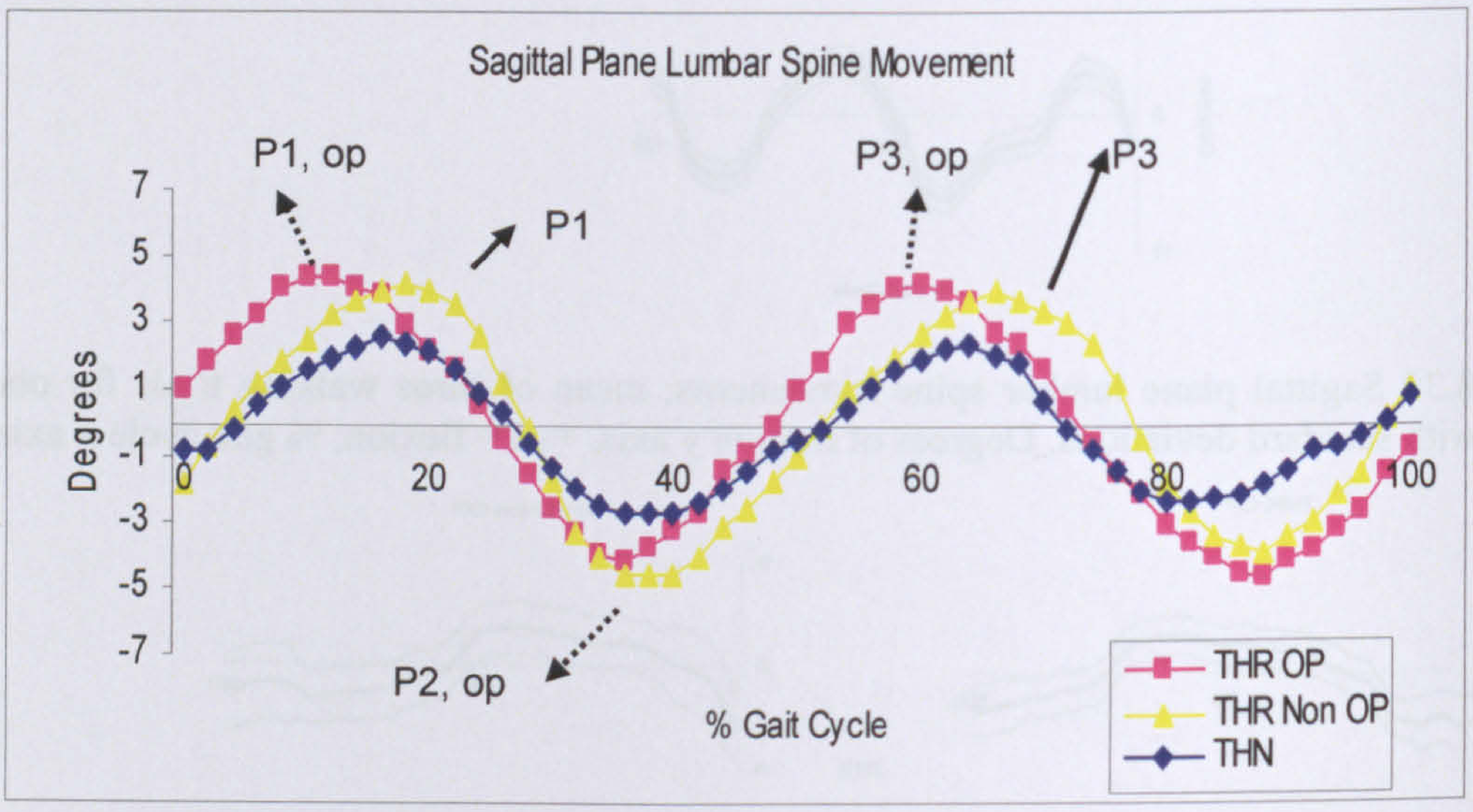


Figure 8.33 Sagittal plane lumbar spine movements; averaged graph for each group, +ve on y axis = forward flexion

Frontal and horizontal plane lumbar spine motion both show patterns for the THR groups which are much flatter than the THN group this represents the norm for these groups and can be more clearly seen in Figures 8.34 and 8.35.

8.4.3 Averaged lumbar spine data per group

Examples of the averaged lumbar spine movements in each plane per group can be seen in Figures 8.33 – 8.35 (p182A& 183A).

Observation of the curves maximal and minimal points shows the small degree of movement available for each group (Table 8.4). Mean range of movement and mean data at heel strike and toe off are represented in section 8.4.4.

Table 8.4 Minimum and maximum values through the averaged lumbar spine movement data curves in the sagittal, frontal and horizontal planes for each of the groups.

		THR op	THR non op	THN
Sagittal	Peak -ve	-4.66	-4.60	-2.64
	Peak +ve	4.40	4.15	2.55
Frontal	Peak -ve	-2.04	-3.06	-4.12
	Peak +ve	6.13	3.50	4.15
Horizontal	Peak -ve	-2.35	-1.95	-2.98
	Peak +ve	2.53	1.83	3.84
All data measured in degrees				

Sagittal plane motion (Figure 8.33) for all three groups follows a similar pattern with two phases of flexion and extension. Both the THR op and THR non op groups appear to have greater range than the THN group, with the first flexion peak (P1, Figure 8.34) from the THR op group occurring before that of the THR non op and THN groups. The first extension peak occurs at a similar percentage of the gait cycle (P2, Figure 8.33) for each of the three groups but the THR op data occurs slightly before that of the THR non op and THN. The second peak flexion (P3, Figure 8.33)

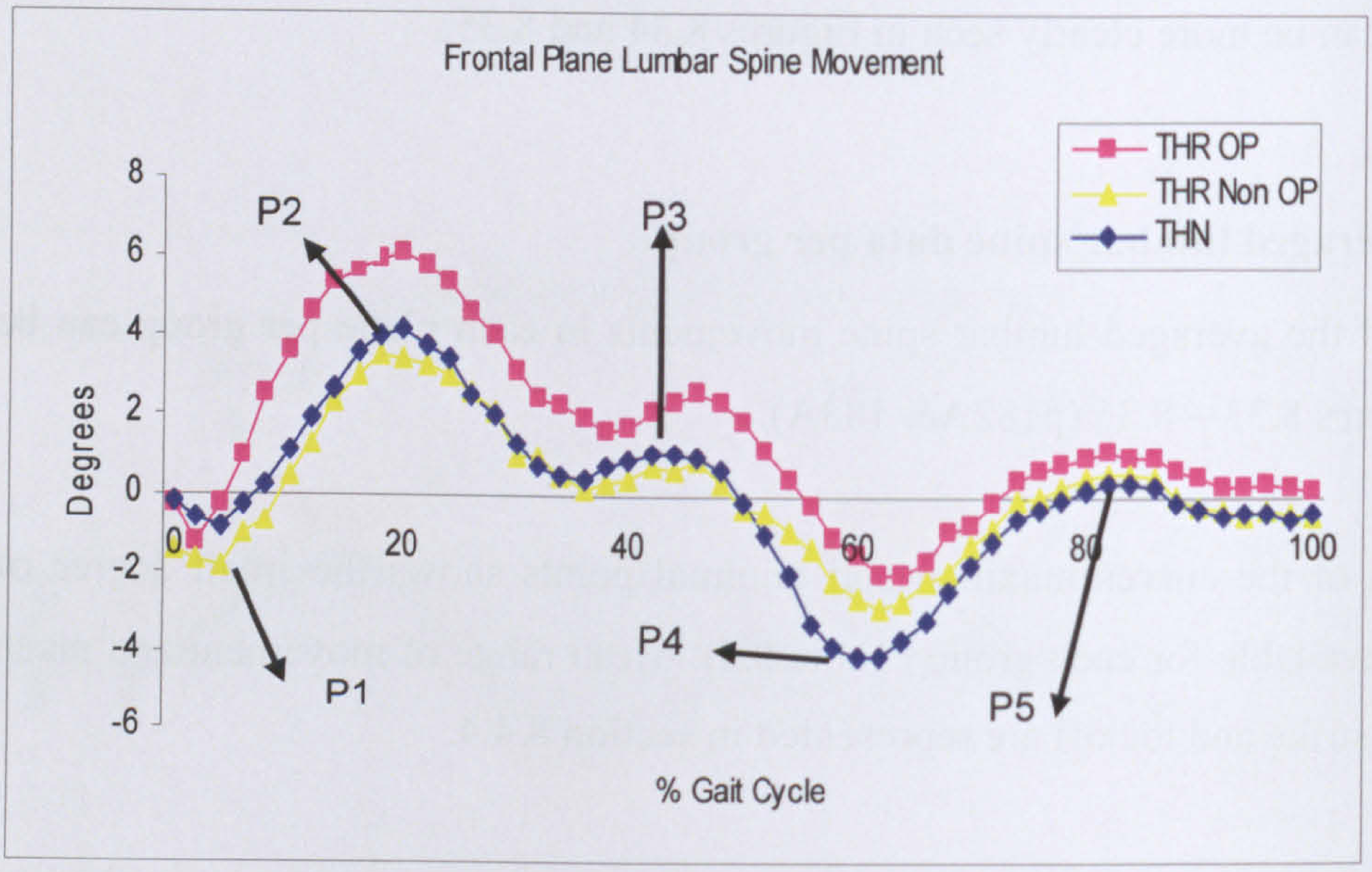


Figure 8.34 Frontal plane lumbar spine movements; averaged graph for each group, +ve on y axis = flexion to same/ weight bearing side

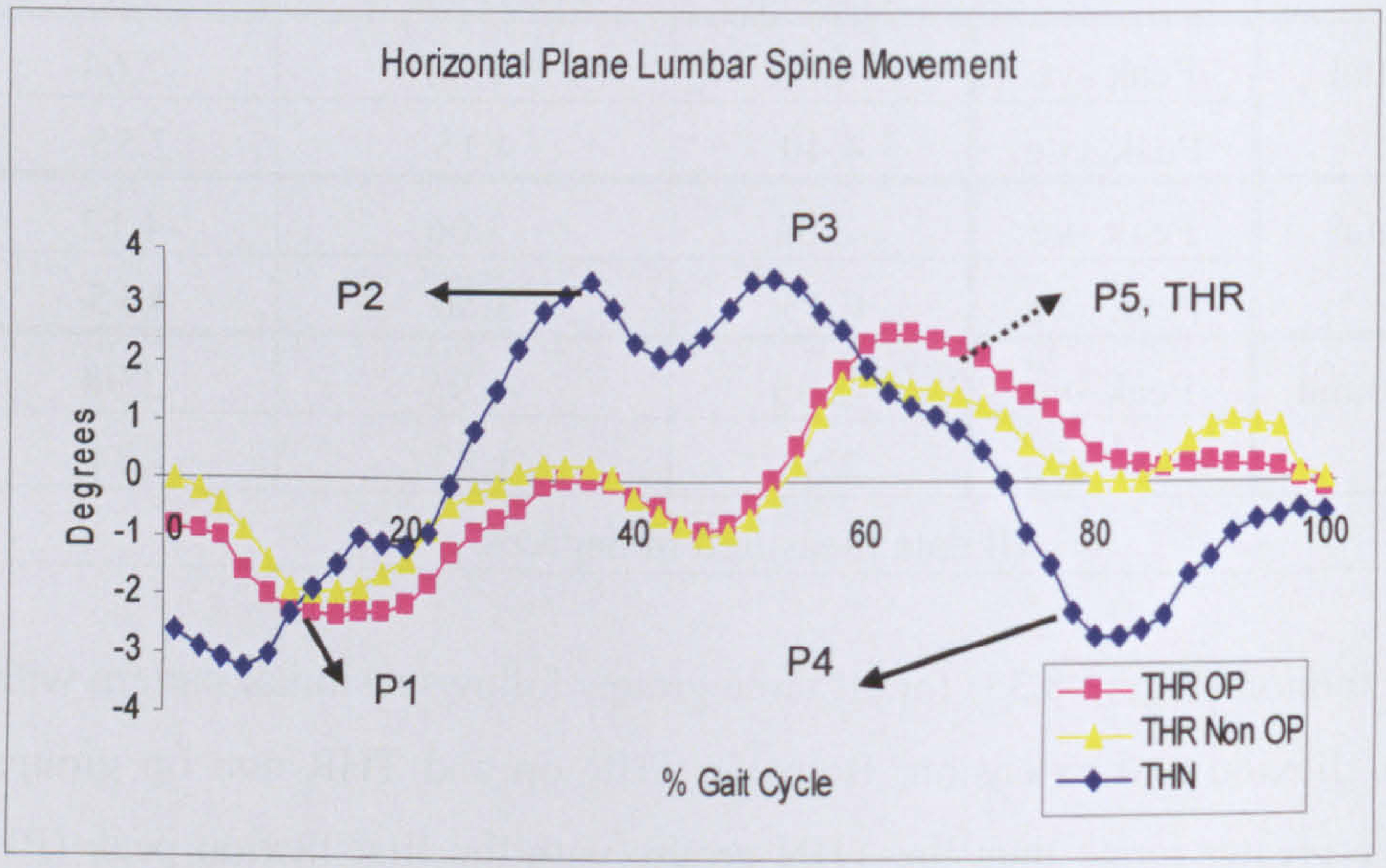


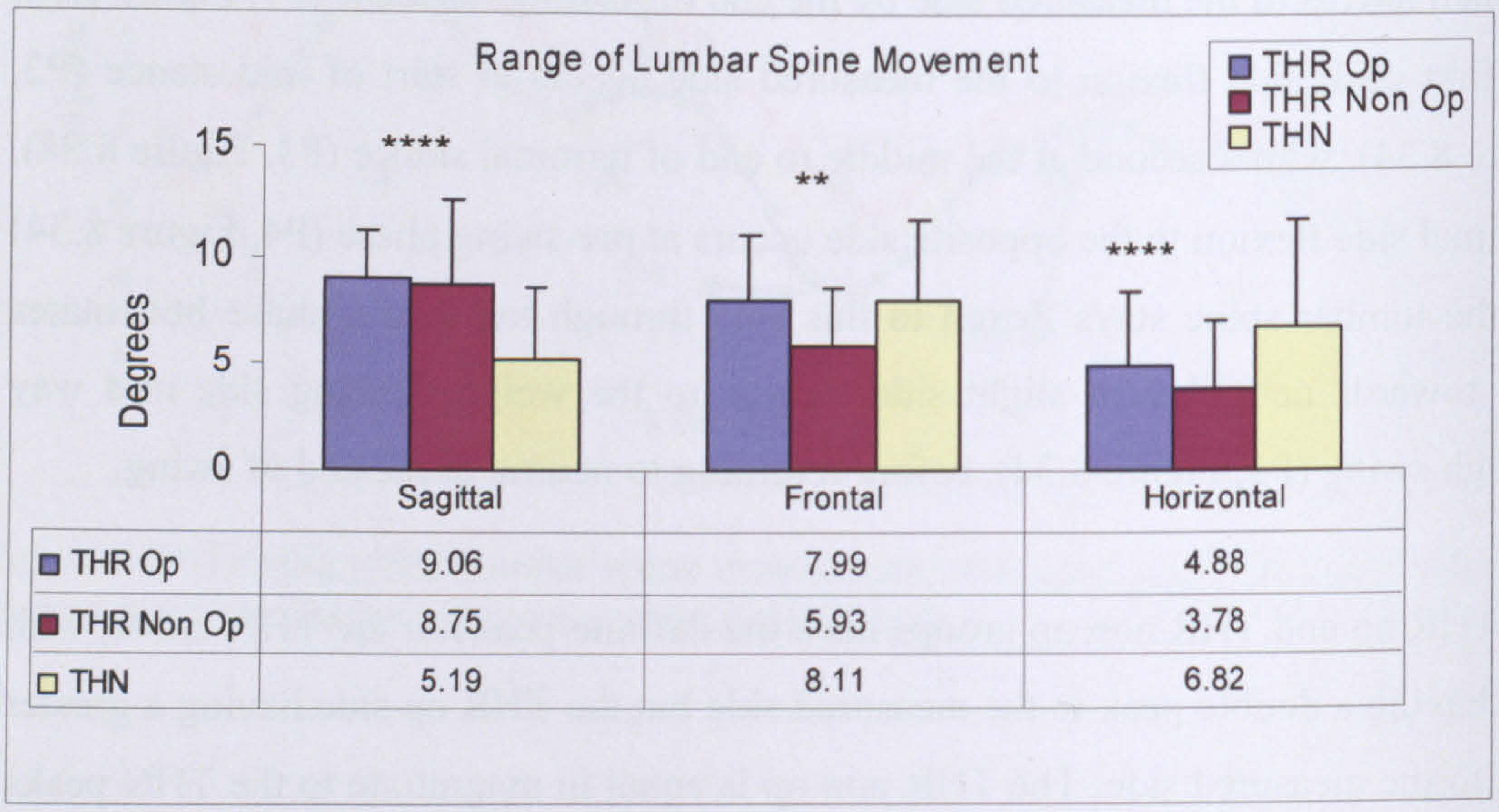
Figure 8.35 Horizontal plane lumbar spine movements; averaged graph for each group, +ve on y axis = rotation to the same side (forward rotation)

again appears before that of the THN and THR non op groups. The second extension peak for the THN group has less magnitude and occurs earlier than either the THR op or non op groups.

Figure 8.34 represents the mean frontal plane lumbar spine movement curves. The THN group follow a pattern starting in lumbar side flexion to the non measured side and then moves to the measured side by the end of loading response (P1, Figure 8.34. The first peak side flexion to the measured side occurs at start of mid stance (P2, Figure 8.34), with a second at the middle to end of terminal stance (P3, Figure 8.34). Maximal side flexion to the opposite side occurs at pre-swing phase (P4, Figure 8.34) and the lumbar spine stays flexed to this side through the swing phase but rotates back towards neutral with slight side flexion to the weight-bearing side mid way through swing (P5, Figure 8.34), before returning to neutral at the end of swing.

The THR op and THR non op groups have the definite peaks of the THN curve, with both having a double peak to the measured side but the THR op side having a greater peak to the measured side. The THR non op is equal in magnitude to the THN peaks (P2 & P3, Figure 8.34). Through out the stance phase the THR op curve follows the pattern of the THN but at all times the magnitude is greater than the THN. However in pre-swing the THR op and non op curve does not reach the same magnitude as the THN but occur at the same time frame. The greatest difference between the patterns occurs through mid stance and terminal stance where the THR op group move more to the weight-bearing side than the THN or THR non op groups. At pre-swing the THN has a much larger excursion into side flexion to the non weight-bearing side.

Horizontal plane lumbar spine motion for the THN group moves into more rotation to the opposite side from heel strike to loading response (P1, Figure 8.35). Then through mid stance rotation to the measured side occurs with the first peak at the start of terminal stance (P2, Figure 8.35), then after a small dip returns to this value at the end of the stance phase and the start of pre-swing (P3, Figure 8.35). Through the swing phase the lumbar spine rotates to the non measured side with the peak occurring at mid swing (P4, Figure 8.35).



	Sagittal	Frontal	Horizontal
THR Op	9.06	7.99	4.88
THR Non Op	8.75	5.93	3.78
THN	5.19	8.11	6.82

Figure 8.36 Averaged overall range of lumbar spine motion for each group; sagittal, frontal and horizontal plane, **** p<0.00001, ** p=0.017,

The THR op and non op curves are similar but do not reach the peak magnitudes of the THN curves for either direction of rotation. Rotation to the same side is particularly affected with the peak magnitude (P5 THR, Figure 8.35) occurring much later than either of the THN peaks (P2, P3). P5 occurs at the end of pre- swing with the lumbar spine remaining rotated to the same side through the swing phase.

8.4.4 Mean lumbar spine range of movement data

To assess the statistical variance in the data sets between groups the data range from each person was averaged for sagittal, frontal and horizontal plane movement through the full gait cycle and at both heel strike and toe off.

Averaged range of movement of the lumbar spine with standard deviations through the gait cycle in the sagittal, frontal and horizontal planes are represented in Figure 8.36. Significant differences were found in the sagittal, frontal and horizontal plane on analysis by one way analysis of variance ($p<0.00001$, $p=0.017$ $p<0.00001$, Figure 8.36) and post hoc t-tests show no significant difference between the THR op and the THR non op groups in the sagittal and horizontal planes but significance ($p=0.014$) was reached in the frontal plane. Significant differences between the THR op and THN and the THR non op and THN groups (Table 8.5) were found in all but the frontal plane, THR op vs THN groups.

Table 8.5 Statistical tests for post hoc testing of range of lumbar spine motion between groups

	THR op vs THR non op	THR op vs THN	THR non op vs THN
Plane	tested by a paired t-test	tested by a non paired t-test	
Sagittal	N/S	p<0.00001	p<0.0002
Frontal	0.014	N/S	p=0.008
Horizontal	N/S	p=0.006	p<0.00001

Key:
THR op:- Operated side of the THR group
THR non op:- Non operated side of the THR group
THN:- control group (R& L data combined)
Bonferroni correction significance at (p<0.017)

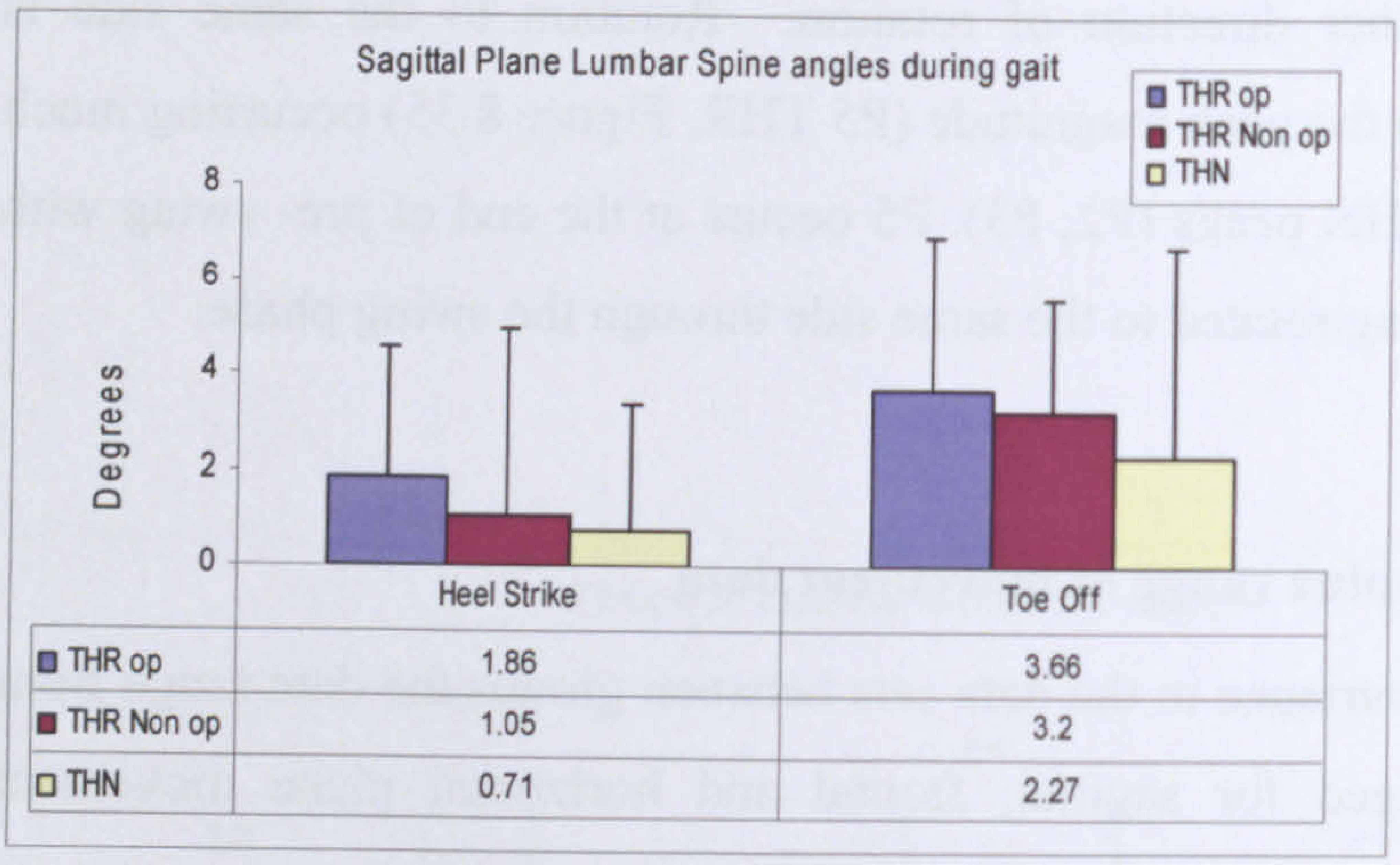


Figure 8.37 Averaged range of sagittal plane lumbar spine motion at Heel Strike and Toe off for each group.

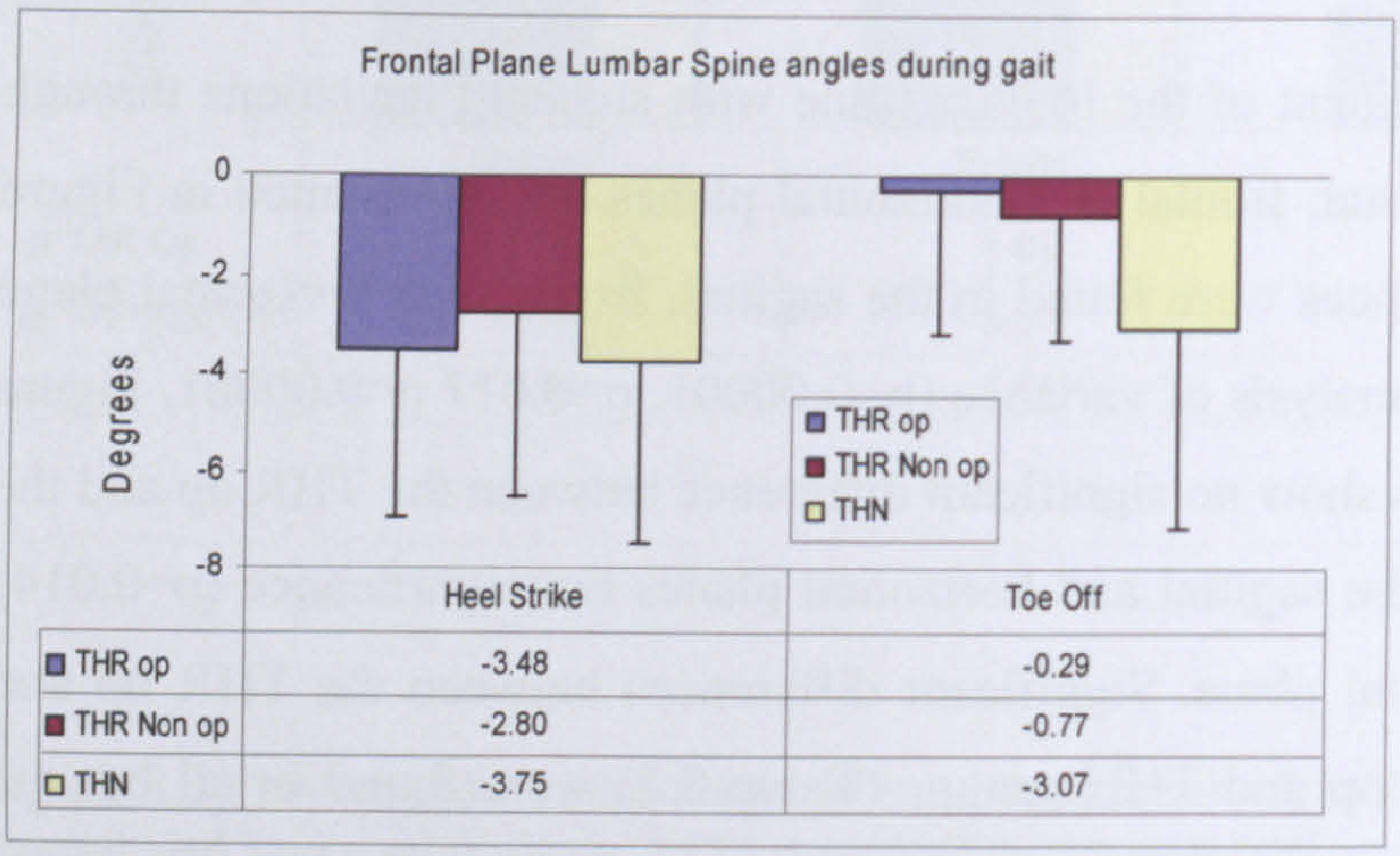


Figure 8.38 Averaged range of frontal plane lumbar spine motion at Heel Strike and Toe off for each group,

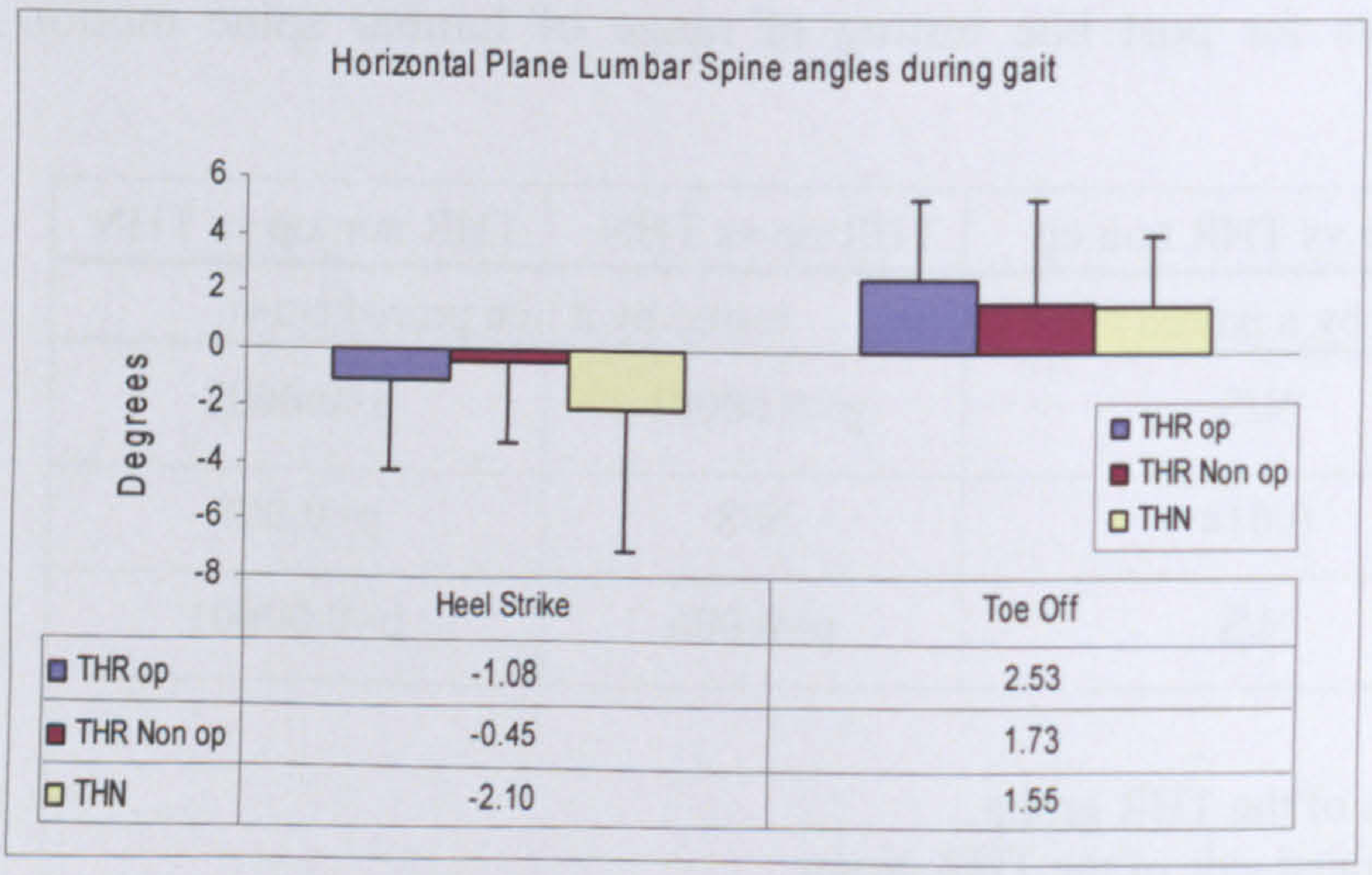


Figure 8.39 Averaged range of horizontal plane lumbar spine motion at Heel Strike and Toe off for each group.

The THN group had a smallest range (5.19±1.06°) of sagittal plane motion than either of the THR groups (9.06±2° op, 8.75±2.08° non op) and a larger range in both the frontal (8.27±1.88°) and horizontal (6.82±2.2°) planes. The THR non op group had the smallest range in the frontal (6.56±2.39°) and horizontal (3.78±1.76°) planes and the THR op group had the largest range in the sagittal plane (9.06±2)°.

Averaged data, with standard deviations, for the key gait events of heel strike and toe off are presented by group for each of the three planes of movement (Figure 8.37 - 8.39). No statistically significant differences between the groups for either heel strike or toe off were found for any of the planes of motion (p= 0.19 – 0.84).

In the sagittal plane the THN group had the smallest degree of sagittal plane motion at heel strike and toe off with the THR op group having the largest. The THN group had the largest mean degree of motion in the frontal plane at heel strike and toe off and the horizontal plane at heel strike. At toe off in the horizontal plane the THN group had the smallest mean movement. The THR non op group had the smallest mean degree of motion at heel strike in the frontal and horizontal plane, but at toe off the operated group had the smallest range in the frontal plane and the largest range in the horizontal plane.

All average movements in each of the planes were accompanied by large standard deviations which may have influenced the analysis demonstrating high variability for all of the groups.

8.4.5 Summary of Lumbar Spine movement results

Summary of lumbar spine movement results

- A significant difference was found between the range of averaged sagittal frontal and horizontal movement on analysis by one way analysis of variance ($p<0.00001$, $p=0.017$, $p<0.00001$). Post hoc testing identified significant differences between the THR groups and THN groups in all bar the frontal plane and between the THR op and non op groups in the frontal plane only.

- Statistically significant differences were found at toe off in the frontal plane ($p<0.0001$) on testing by one way analysis of variance and post hoc testing by t-tests identified significance between each of the groups THR op vs Non op ($p<0.00001$), THR op vs THN ($p<0.00001$) and THR non op vs THN ($p=0.0003$). No significant differences were found in either the sagittal or frontal planes at toe off and for all planes at heel strike.

- Observation of the curve patterns (Figures 8.33 – 8.35) show that the THR op group has an altered pattern to the THN group in all three planes of movement. The THR non op group are in more flexion than the THN group and have less frontal plane movement. In the horizontal plane less rotation is found at the start of the stance phase but this changes to an increased in backward rotation at the end of stance and the swing phase.

8.5 INTERACTION OF MOVEMENT DATA: ANGLE – ANGLE DIAGRAMS

As presented in section 4.2.3 angle-angle diagrams give a representation of the interaction of one movement with another. Pairs of curves from each plane of movement for the hip, pelvis and lumbar spine are represented during walking for each of the three groups THR op, THR non op and THN. The pairs of curves to be explored for each group are:

Sagittal Plane
Hip movement versus sagittal plane lumbar spine movement
Hip movement versus sagittal plane pelvic movement
Pelvic movement versus sagittal plane lumbar spine movement

Frontal plane
Hip movement versus frontal plane lumbar spine movement
Hip movement versus frontal plane pelvic movement
Pelvic movement versus frontal plane lumbar spine movement

Horizontal plane
Hip movement versus horizontal plane lumbar spine movement
Hip movement versus horizontal plane pelvic movement
Pelvic movement versus horizontal plane lumbar spine movement

The curves will be presented in the order above with each of the group data superimposed onto one graph (Figure 8.40 - 44, p187A – 189A).

Representations of single angle- angle diagrams can be found in Appendix U

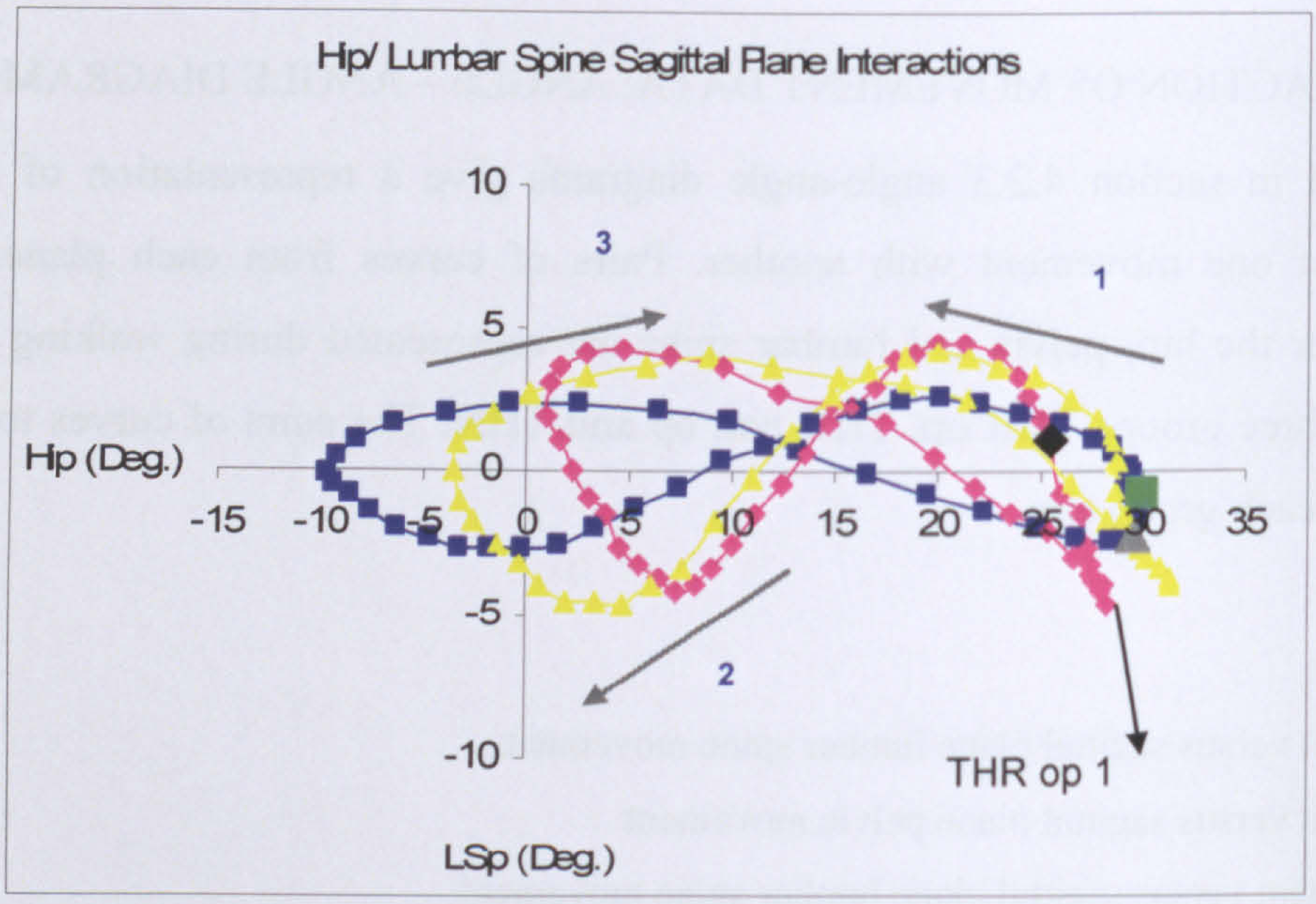
Group Comparisons:

These were undertaken to show comparison of group data and can be found in Appendix U

Sagittal, Frontal and horizontal plane operated hip (THR op) versus non operated hip (THR non op) movement,

Sagittal, Frontal and horizontal plane operated hip (THR op) versus THN movement,

Sagittal, Frontal and horizontal plane non operated hip (THR non op) versus THN movement,



Key:
THR op ━
THR Non op ━
THN ━
THN Direction of movement 1,2,3 direction order

Coloured diamonds denote Heel strike for each of the three data sets:
THR op Black, THR non op Grey, THN Green

Figure 8.40 Angle-angle sagittal plane diagrams of hip/ lumbar spine movement during one gait cycle. All movements in degrees, Hip +ve on x axis = flexion,
LSp +ve on y axis = forward flexion.

Angle-angle diagrams represent the pattern of movement between two angles and start at the beginning of a time frame: in this case the start of the gait cycle. Each symbol across the line represents a time component, if the symbols lie closer together then the time frame is occurring faster than when they do not. The axes ranges for each plane have been chosen to give the best visual representation of the movement pattern. The axes for each of the angle-angle diagrams in each plane are identical. The start point for each movement pattern is represented by a contrast coloured symbol: THR op Black, THR non op Grey, THN Green.

Sagittal plane movement on the abscissa (x) axis in the positive direction represents hip flexion or anterior pelvic tilt, frontal plane movement on the abscissa in the positive direction represents hip abduction or pelvic tilt to the same side and horizontal plane movement on the abscissa in the positive direction represents hip or pelvic rotation to the same side.

Sagittal plane movement on the ordinate (y) axis in the positive direction represents lumbar spine flexion or anterior pelvic tilt, frontal plane movement on the ordinate in the positive direction represents lumbar spine side flexion to same side or pelvic tilt to the same side and horizontal plane movement on the ordinate in the positive direction represents lumbar spine or pelvic rotation to the same side.

All movements in the negative direction denote the opposite to the above.

8.5.1 Sagittal Plane Interactions

Angle-angle diagrams in the sagittal plane (hip/ lumbar spine and hip/ pelvis interactions) show differences between the groups but the patterns are very similar (Figure 8.40). The pattern for the THN group for hip/ lumbar spine has a greater dispersion/ range and is much smoother than the other groups but overall the timing and relationships are the same. The differences occur in the hip movement rather than lumbar spine demonstrated by the shorter squatter pattern. Movement is cyclical forming a butterfly shape demonstrating two phases of flexion and two of extension for each segment. The THR op and non op patterns follow this shape but do not have the same equality of shape as the THN group.

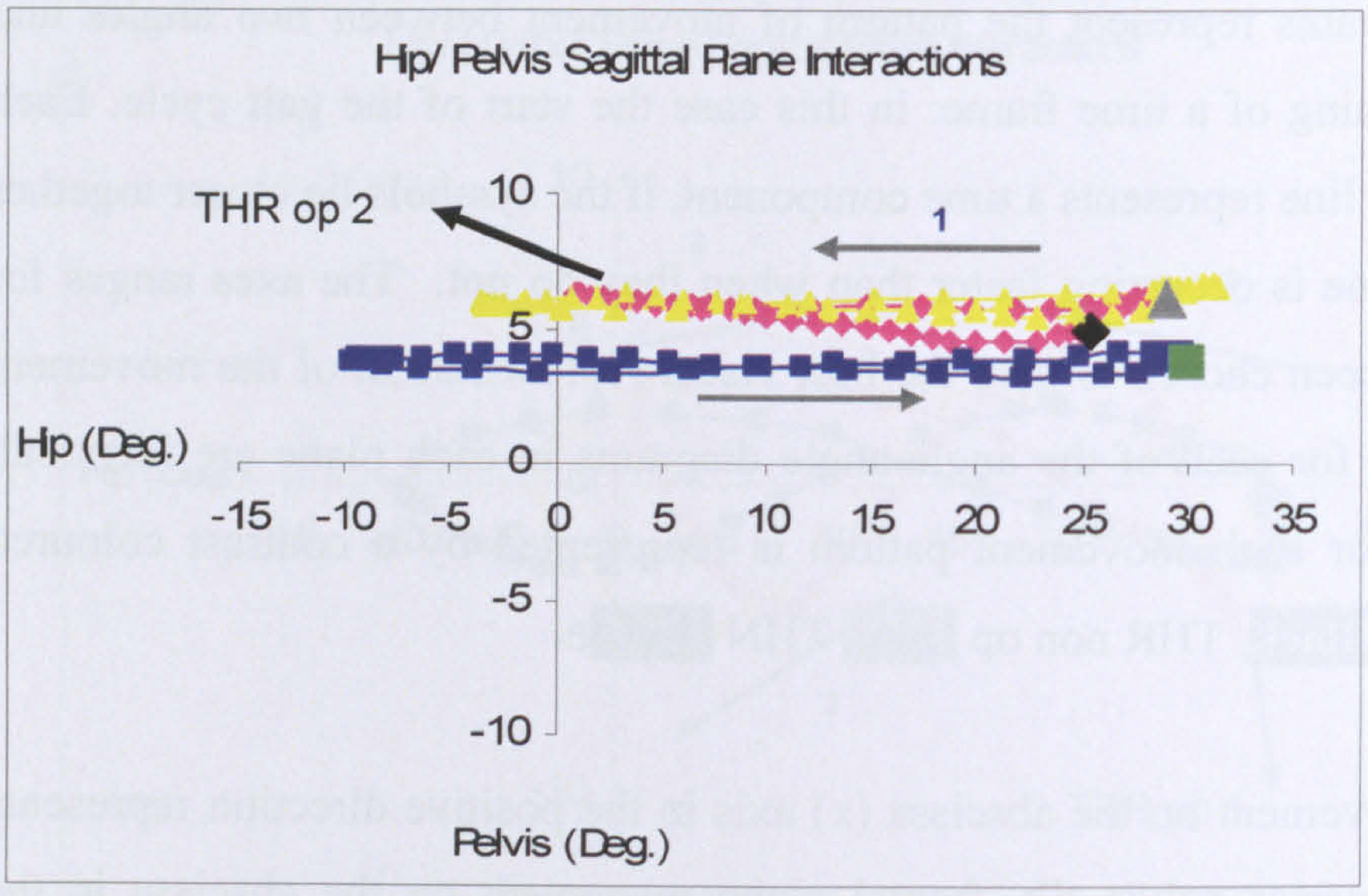


Figure 8.41 Angle-angle sagittal plane diagrams of hip/ pelvis movement during one gait cycle. All movements in degrees, Hip +ve on x axis = flexion, Pelvis +ve on y axis = anterior tilt.

Key for Figure 8.41 and 8.42:

Coloured diamonds denote Heel strike for each of the three data sets:
THR op Black, THR non op Grey, THN Green.
THN Direction of movement, **1** = 1st direction →

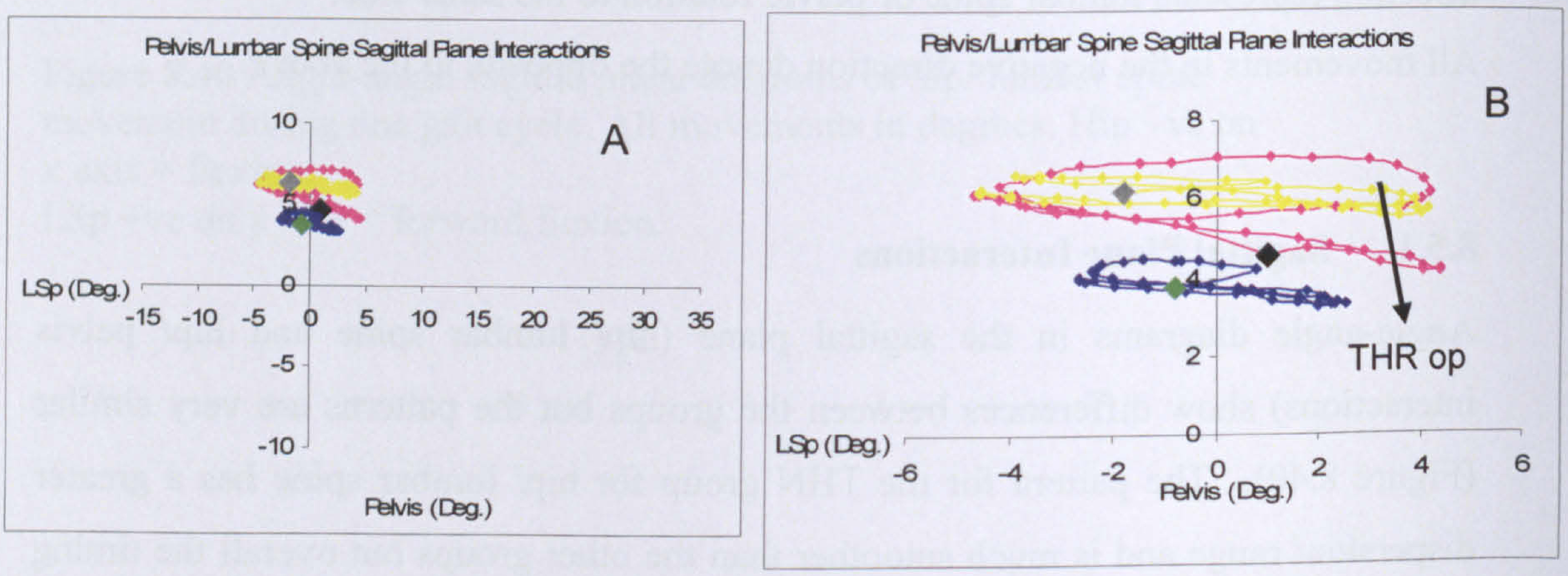


Figure 8.42 Angle-angle sagittal plane diagrams of pelvis/ lumbar spine movement during one gait cycle with two representations for ease of viewing A) as per other sagittal plane view (Figure 8.40, B) smaller axes scale. All movements in degrees Lumbar spine +ve on x axis = forward flexion, Pelvis +ve on y axis = anterior tilt.

The THN pattern shows that the hip goes from maximum flexion at the start of the gait cycle with the lumbar spine in extension and moves into extension through mid stance with the lumbar spine going into flexion. Maximum lumbar extension occurs in the middle of mid stance and holds until the end of this phase whilst the hip continues into full extension. The hip moves into maximum extension whilst the lumbar spine returns to the neutral position before both the hip and lumbar spine flex again. The lumbar spine moves into extension again at the start of the swing phase whilst the hip slowly extends. From mid swing through terminal swing both the THR op and THR non op patterns show a faster transition than the THN pattern with the symbols bunching together and a small peak of movement occurs at the end of the pattern (THR op 1).

Hip/ pelvis patterns (Figure 8.41) are similar for all group data but the THN shows more hip range, whilst the THR op and THR non op show more pelvic movement. The THR op data shows a flatter curve particularly through end of the stance phase (THR op 2, Figure 8.41) when the pelvis has limited movement.

The ranges are small for pelvis/ lumbar spine interaction therefore they are difficult to interpret using the same scale as the hip/ lumbar spine and hip/ pelvis figures. To allow greater analysis the figure is also represented with smaller axes ranges (Figure 8.42 A & B).

The pelvis/ lumbar spine interactions show disparity between the group patterns. The pattern for the THR op group is more widespread and the timing of phases is slower (wider spacing between symbols) than either the THR non op or THN patterns (Figure 8.42B). The THR op pattern changes at the start of terminal stance having a larger sweep of movement from this point into preswing, initial swing and mid swing, this is represented by the hoop of pink points (THR op 3) which is not seen in either of the other groups. The smoothness of this hoop indicates that the movement occurs both in the pelvis and the lumbar spine.

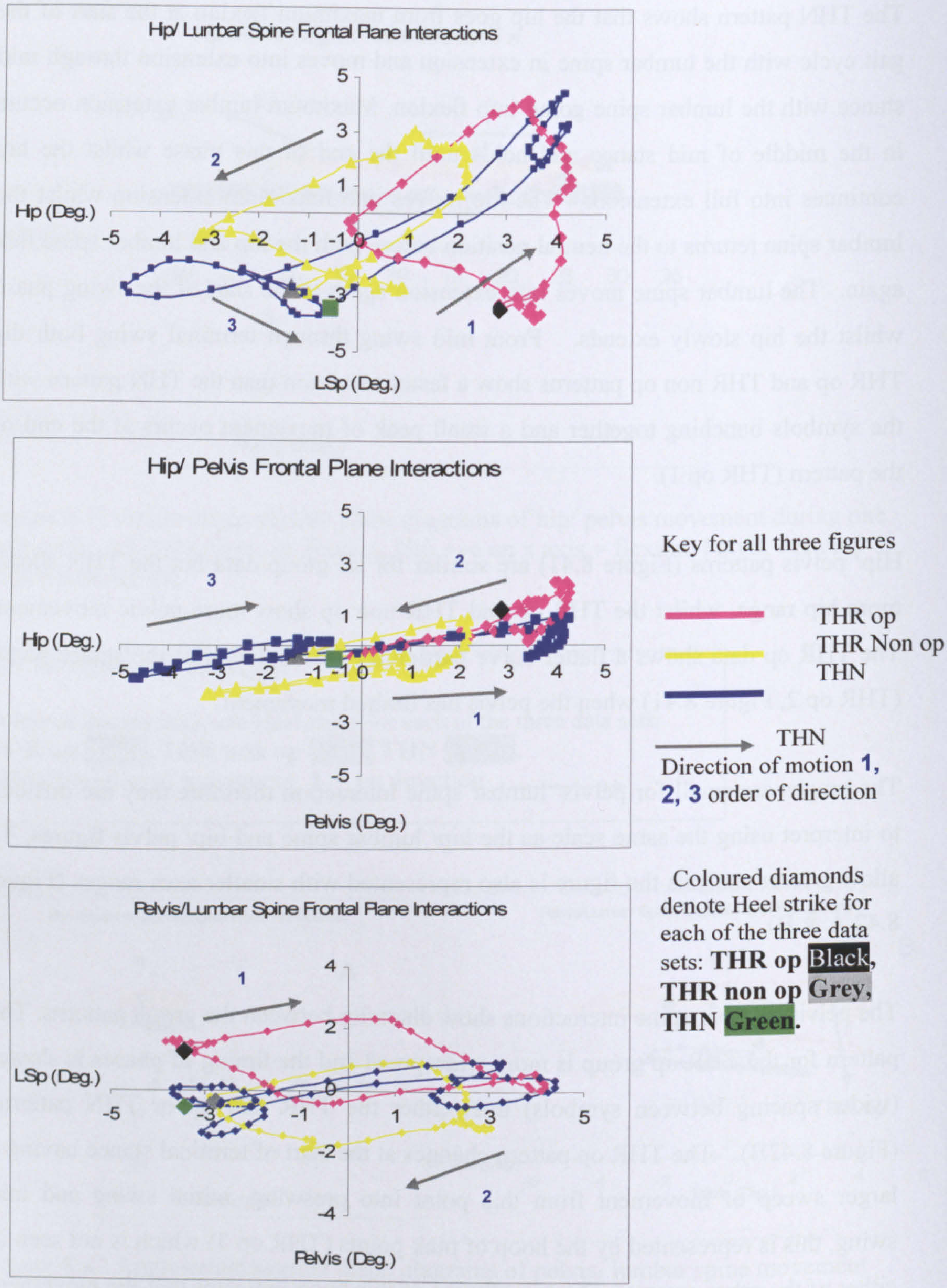


Figure 8.43 Angle-angle frontal plane diagrams of hip/ pelvis, hip/ lumbar spine and pelvis/ lumbar spine movement during one gait cycle. All movements in degrees Hip +ve on x axis = adduction, Pelvis +ve on y axis = tilt to same (weight bearing) side, Lumbar spine +ve on x + y axis = flexion to same/ weight bearing side.

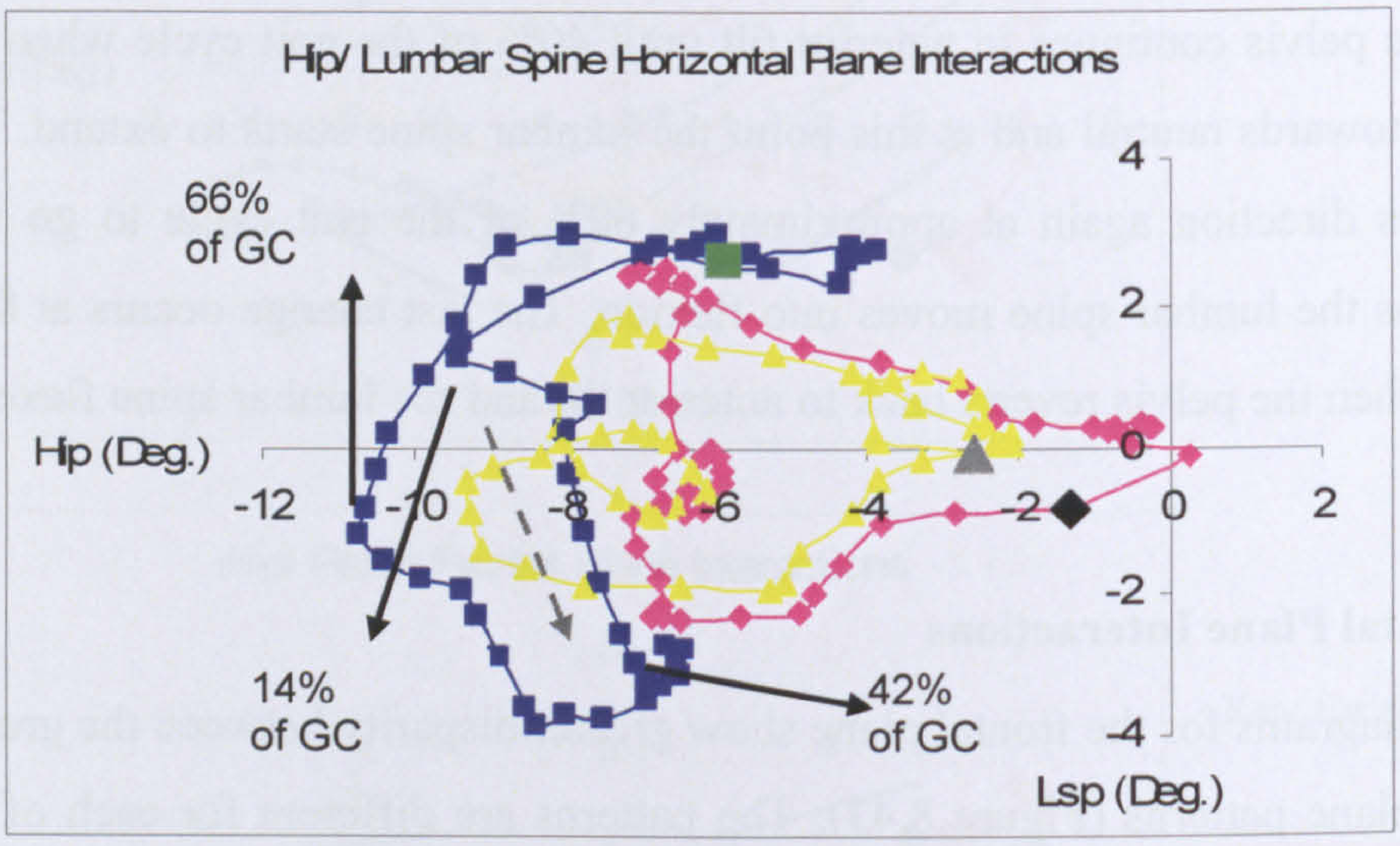
The THR Non op pattern (yellow) is different to the THN as the movement is greater in magnitude but the overall patterns are similar. The THN pattern starts with both the pelvis and lumbar spine increasing in movement; the pelvis into anterior tilt and the lumbar spine into extension. At 20% of the gait cycle the lumbar spine starts to flex whilst the pelvis continues to anterior tilt until 40% of the gait cycle when the pelvis moves towards neutral and at this point the lumbar spine starts to extend. The pelvis changes direction again at approximately 60% of the gait cycle to go into posterior tilt as the lumbar spine moves into flexion. The last change occurs at 80% of the cycle when the pelvis reverts back to anterior tilt and the lumbar spine flexes.

8.5.2 Frontal Plane Interactions

Angle-angle diagrams for the frontal plane show greater disparity between the groups than sagittal plane patterns (Figure 8.43). The patterns are different for each of the groups especially for hip/ lumbar spine and pelvis/ lumbar spine interactions. The interactions for the hip and pelvis show that the THN group data have a greater range of hip movement then the others, however all three data sets show faster movement (a bunching of data) through mid stance followed by a slower transition into terminal stance and pre swing.

Hip/ lumbar spine interactions in the frontal plane demonstrate similar patterns for the THR op and non op data sets but these are different for the THN group. The interaction for all three data sets is biphasic with two slow and two fast periods during the gait cycle. The THN pattern demonstrates slow movement at the start of the gait cycle which increases in speed through mid stance then slows through terminal stance but speeds up again in the swing phases. There is a larger degree of excursion in hip movement than lumbar spine as the hip moves into adduction the lumbar spine goes into side flexion to the same side, the reverse happens during the transition phase of preswing and the swing phases. The pattern is more open in the latter part of the cycle.

Interactions for the THN data sets for the pelvic/ lumbar spine shows a very different pattern to that of the THR op and non op data sets. The THN group has more lumbar



Key:

THR op ▬

THR Non op ▬

THN ▬

THN Direction of motion from 14 - 42% of gait cycle - - - -▸

Coloured diamonds denote Heel strike for each of the three data sets:
THR op Black, THR non op Grey, THN Green.

Figure 8.44 Angle-angle horizontal plane diagrams of hip/ lumbar spine movement during one gait cycle. All movements in degrees Hip +ve on x axis = medial rotation, Lumbar spine +ve on y axis = forward rotation to the same side.

spine movement than pelvis whilst the THR op and non op groups are very similar. The THN pattern of movement shows a quadrant of movement where at each corner the pelvis and lumbar spine move in different directions. The first quadrant at 16% gait cycle shows the pelvis and lumbar spine moving into side tilt to the same side then quickly through mid stance the direction changes with the pelvis titling to the opposite side and the lumbar spine remains in neutral for the start of the second quadrant. Then the pelvis and lumbar spine tilt again to the same side and then at the end of mid stance the both tilt away, however these movements are very small and may represent a setting of the lumbar spine and pelvis after and before larger movements occur. The third and fourth quadrants occur towards the end of the cycle with a very similar pattern to those at the start of the cycle.

The THR op and non op data sets do not have this quadrant pattern, describing a single rectangle of movement, both patterns have a phase where movement is faster, one at approximately 44% of the cycles and the other at 64% for the THR non op group and at 90% of the gait cycle for the THR op group. The magnitude of the rectangular shapes is similar but the THR op group have more pelvic tilt to the measured side than the THR non op group and vice versa.

8.5.3 Horizontal Plane Interactions

The patterns for horizontal plane movements for each of the three interactions (hip/ lumbar spine, hip/ pelvis and pelvis/ lumbar spine) are all different (Figures 8.44-8.45). The patterns for the THR op and non op groups are predominantly similar but these differ from the THN patterns.

The THR groups have more hip movement during the hip/ lumbar spine interactions (Figure 8.44), whilst the THN data set has more lumbar spine rotation than the THR groups. The interesting points on the THN pattern occur at 42% and 66% of the cycle. At 42% the hip and the lumbar spine rotate a very small degree and movement occurs quickly. At this point the hip lies in lateral rotation and the lumbar spine in rotation to the opposite side. Whilst at 66% of the cycle there is a complete change of direction from the hip laterally rotating and the lumbar spine rotating to the same

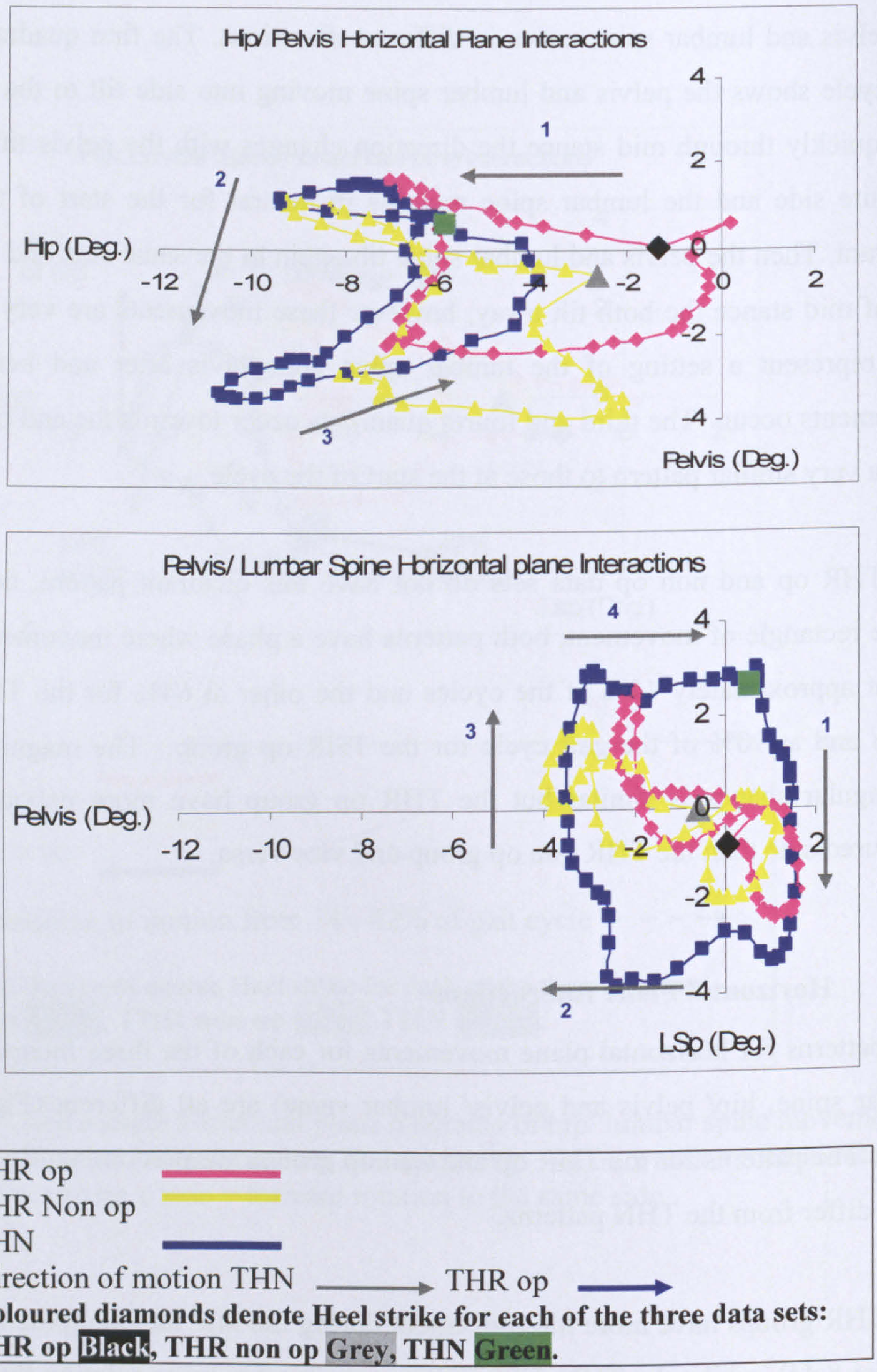


Figure 8.45 Angle-angle horizontal plane diagrams of hip/ pelvis and pelvis/ lumbar spine movement during one gait cycle. All movements in degrees, Hip +ve on x axis = medial rotation, Pelvis +ve on x + y axis = forward rotation, Lumbar spine +ve on y axis = rotation to the same side.

side. The whole pattern for the THN group lies in more lateral hip rotation than either of the other groups. The THR groups lie in less lateral rotation with the hip showing a smaller degree of hip lateral rotation and lumbar spine rotation at the start of the cycle.

At the start of the gait cycle both the THR groups move into lateral rotation at the hip with lumbar spine rotation to the opposite side, then at mid stance the hip and lumbar spine change direction of rotation. At this point the movement stabilises before changing again at approximately 56% of the gait cycle for a small period of time. Movement changes again at 60% of the cycle to remain in the same degree of lumbar spine movement but into less lateral rotation at the hip.

The patterns of movement between the hip and pelvis (Figure 8.45) show the least disparity of the horizontal plane interactions. Movement for the THN groups lies in more lateral rotation of the hip and the THR groups rotate more towards neutral at the hip. The degree of pelvic movement is similar between the groups. The THN pattern shows lateral rotation at the hip at the start of the gait cycle with minimal pelvic movement to the same side. At 14% of the cycle the hip starts to loose lateral rotation but the pelvis remains in slight rotation to the same side, then at 40% of the cycle the hip rotates slowly into more lateral rotation accompanied by rotation of the pelvis to the opposite side. This ends at 66% of the gait cycle with both segments moving in the opposite direction.

Although the THR groups follow a similar pattern the slope of the interaction is less pronounced indicating that there was a larger degree of movement in one of the segments, in this case the pelvis.

The degree of pelvic movement during pelvis/ lumbar spine interaction is very similar for all three groups but the THR groups (pink and yellow) have less lumbar spine movement (Figure 8.45). The THN group (blue) has a square pattern, where there are two periods of movement of the lumbar spine and two of the pelvis. From heel strike, the lumbar spine rotates to the opposite side whilst the pelvis stays in slight rotation to the same side. At approximately 34% of the cycle the pelvis rotates to the opposite side and the lumbar spine remains in rotation to the opposite side. At 56% of the cycle the lumbar spine rotates towards the mid line and continues to rotate to the same side until 82% of the cycle, whilst the pelvis remains in rotation to the opposite side. From 82% of the cycle the pelvis rotates to the mid line and then to the same side whilst the lumbar spine stays in rotation to the same side.

The pattern for the THR groups rotates the pelvis to the same side with minimal lumbar spine movement before the lumbar spine starts to rotate to the opposite side with some rotation of the pelvis to the same side. At 24% of the cycle the pelvis rotates back towards neutral whilst the lumbar spine stays in neutral. Then the pelvis starts to rotate to the opposite side again with minimal change in lumbar spine position until approximately 52% of the cycle when the lumbar spine rotates to the same side whilst the pelvis remains static. There is then a setting pattern (Figure 8.45, p192A) where the pelvis and lumbar spine rotate through a small degree of movement before returning the pelvis and lumbar spine to neutral.

8.5.4 Summary of Angle – angle diagrams

Summary of angle-angle diagrams

- Sagittal plane angle-angle diagrams of hip/ lumbar spine and pelvis/ lumbar movements show differences between the data for the three groups. The patterns for hip/ lumbar spine interactions are similar for all three groups but the range of the data is different between the groups, with the THR op group showing the greatest difference when compared to the THN group.
- Sagittal plane group patterns of movement between the pelvis/ lumbar spine show differences between the THR and the THN groups. The THR patterns differ in range and timing to the THN pattern.
- Hip/ pelvis interactions in the sagittal plane show few differences between the three groups.
- All frontal patterns for hip/ lumbar spine, hip/ pelvis and pelvis/ lumbar spine differ between the three groups, for both range and timing with the hip/ pelvis interaction showing the smallest differences. The pelvis/ lumbar spine interactions in the THN group show four clear points of change of interaction and faster movement which are not present in the patterns for the THR groups.
- Movement patterns in the horizontal plane are similar for the THR groups for hip/ lumbar spine and hip/ pelvis interactions but the THN group had more movement and the pattern is more contained.
- Horizontal plane pelvic/ lumbar spine interactions for the THR groups showing a distinctive pattern at the start and end of single limb support. The THN group do not show this pattern.

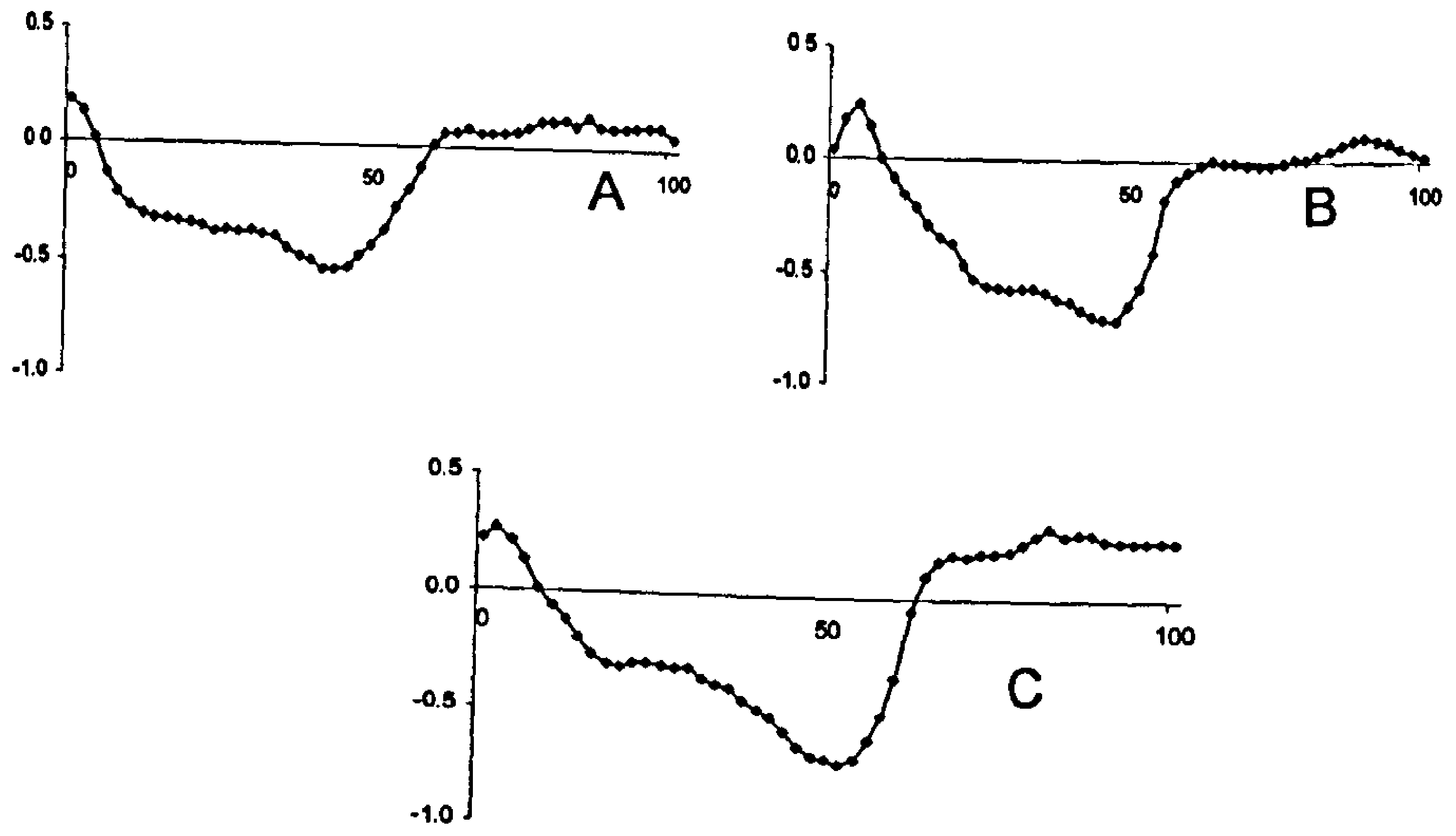


Figure 8.46
Sagittal plane hip moments; individual moment time graphs; +ve on y axis = flexion
A=THR op
B=THR Non op
C=THN

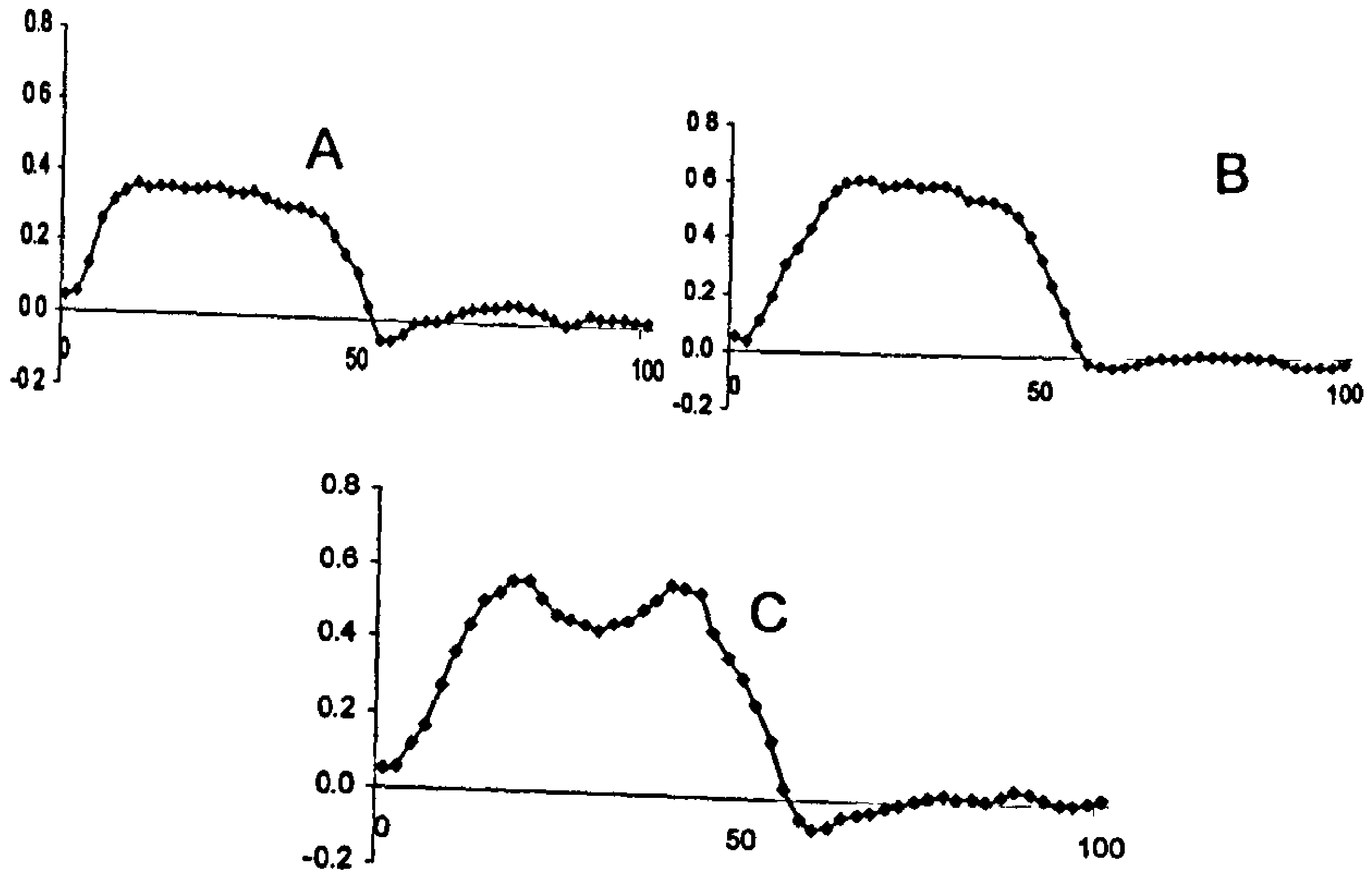


Figure 8.47
Frontal plane hip moments; individual moment time graphs; +ve on y axis = abduction
A=THR op
B=THR Non op
C=THN

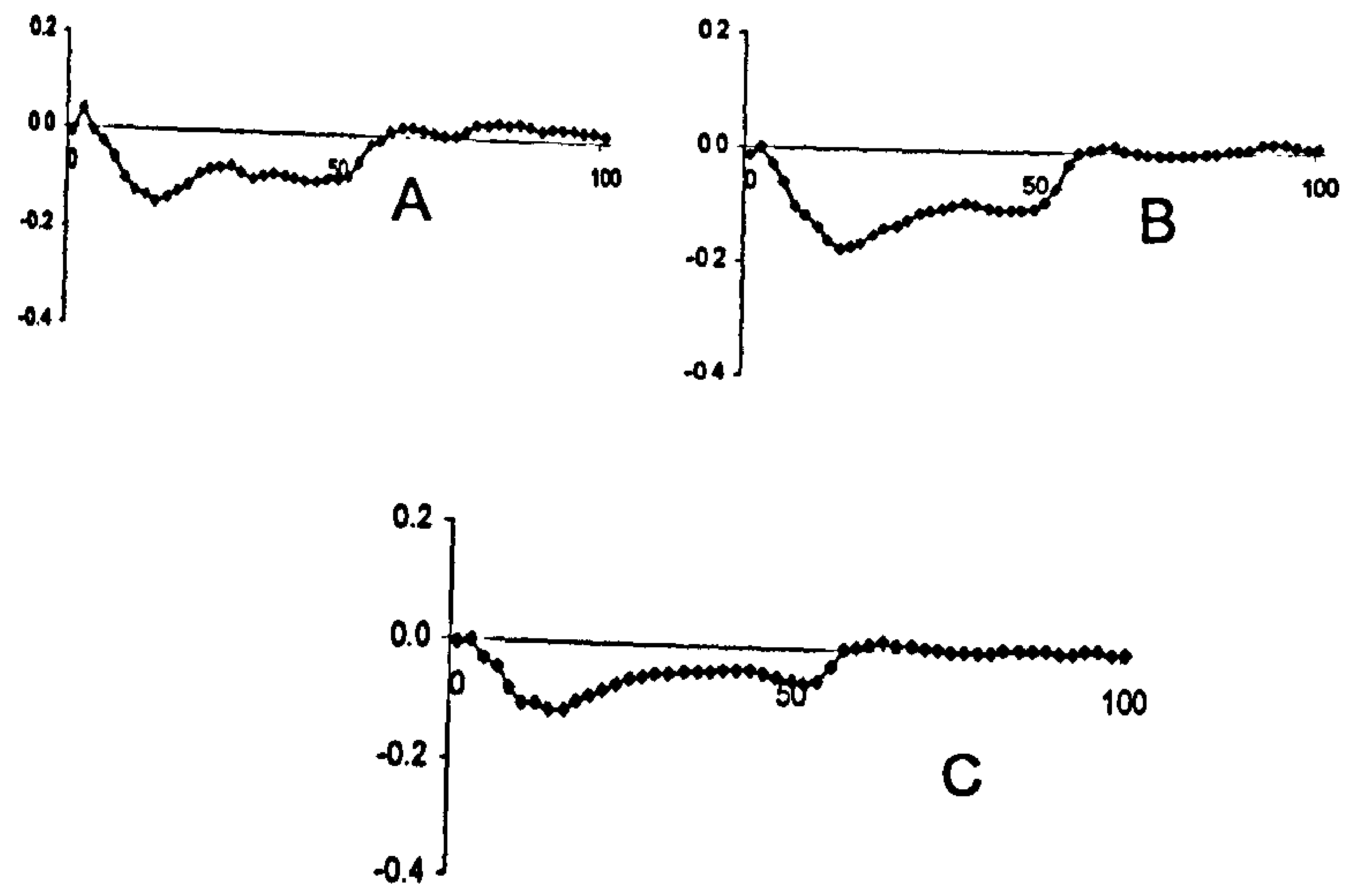


Figure 8.48
Horizontal plane hip moments; individual moment time graphs; +ve on y axis = medial rotation
A=THR op
B=THR Non op
C=THN

Time is represented as 100% of the gait cycle is on the x (abscissa) axis and internal hip moments (Nm/Kg) on the y (ordinate) axis for all three figure.

8.6 HIP JOINT MOMENTS

Mean group data is presented in Appendix V. Tests for normal distribution and statistical analysis of the mean data is also presented in Appendix V.

8.6.1 Individual hip data graph per group

Representative moment graphs for each of the groups are displayed in Figures 8.46 - 8.48. Examples of each hip moment curve from one individual from each of the groups during gait for each hip movement in each plane: sagittal, frontal and horizontal. These individuals are representative of their respective group. Time is represented as 100% of the gait cycle is on the X (abscissa) axis and internal joint moments (Nm/Kg) on the y (ordinate) axis. Each graph starts at initial/ heel contact. Patterns of moment between the groups will be discussed when the averaged curves are presented in section 8.6.3. Group mean data is represented in Appendix V.

8.6.2 Averaged hip angle moment time graphs per individual

Hip joint moments from each person were collected over three gait cycles for all three planes of motion. Averaged hip moment data graphs for a representative individual for each group for each plane are presented in Figures 8.49 – 51 (p196A). All joint moments were normalised to body mass. Mean data is represented by the mid line in each graph with the lines on either side denoting one standard deviation.

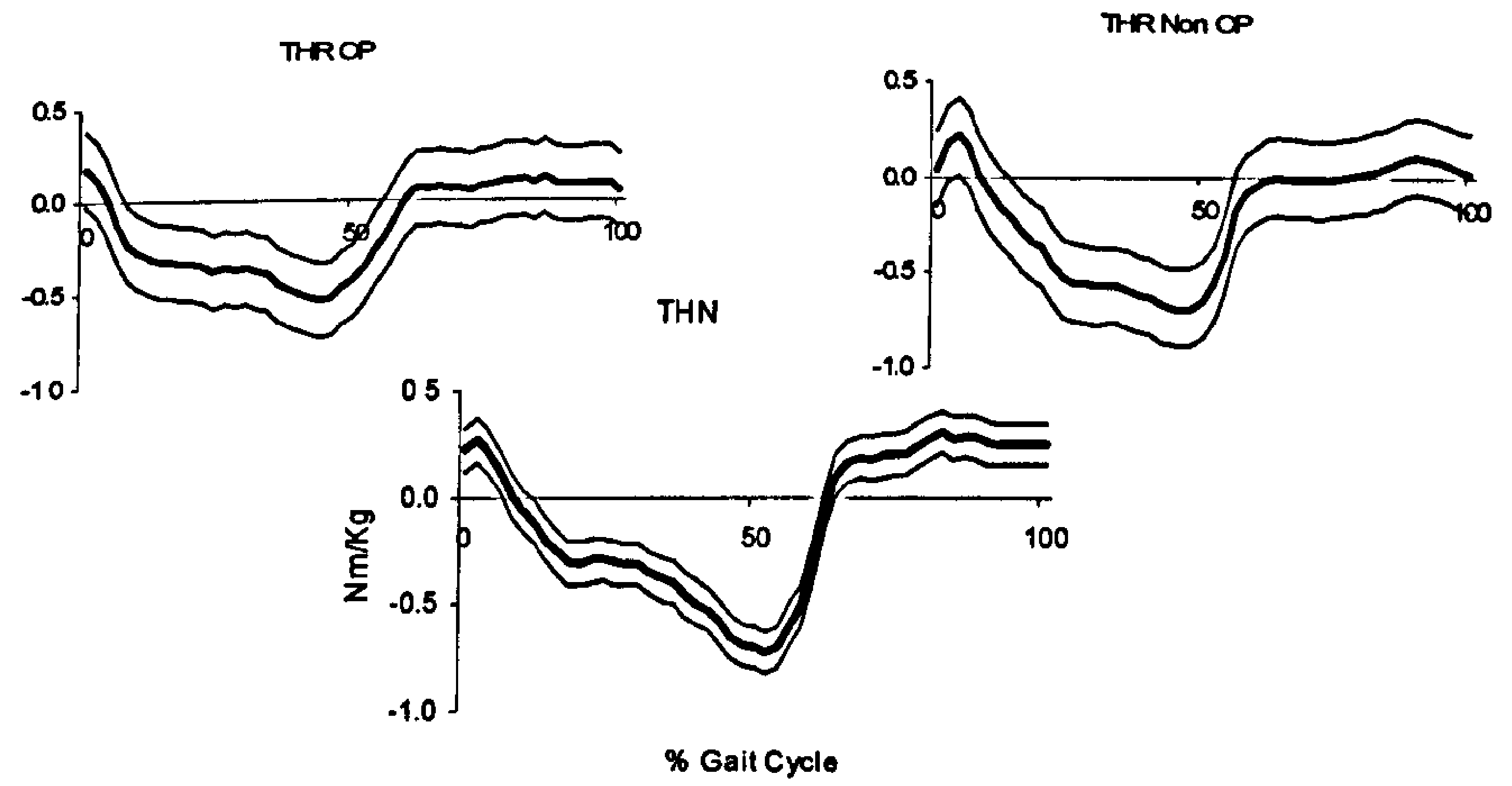


Figure 8.49 Sagittal Plane Hip moment patterns; average of three walking trials for one person with standard deviations, y axis (Nm/Kg), x axis % gait cycle

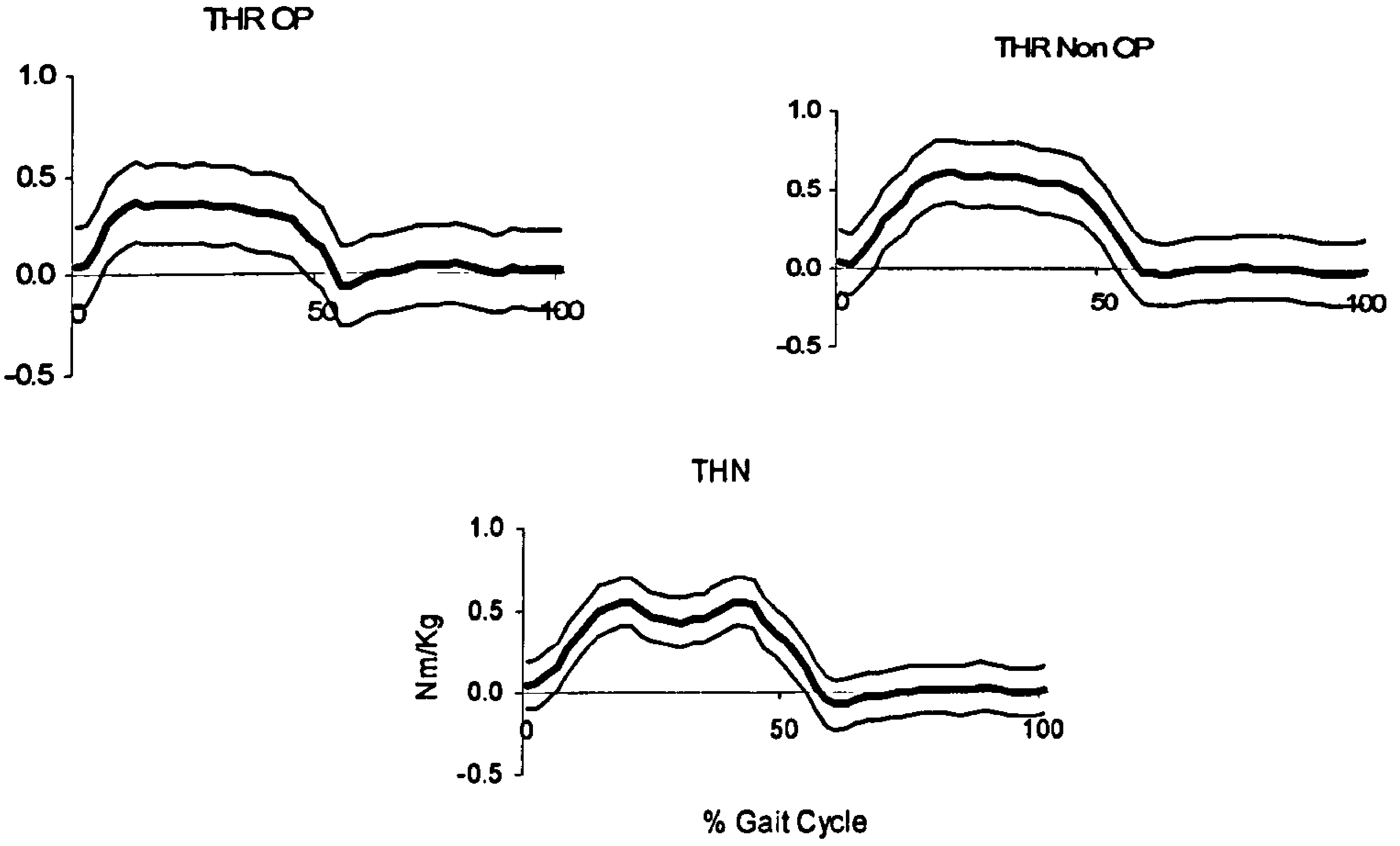


Figure 8.50 Frontal Plane Hip moment patterns; average of three walking trials for one person with standard deviations, y axis (Nm/Kg), x axis % gait cycle

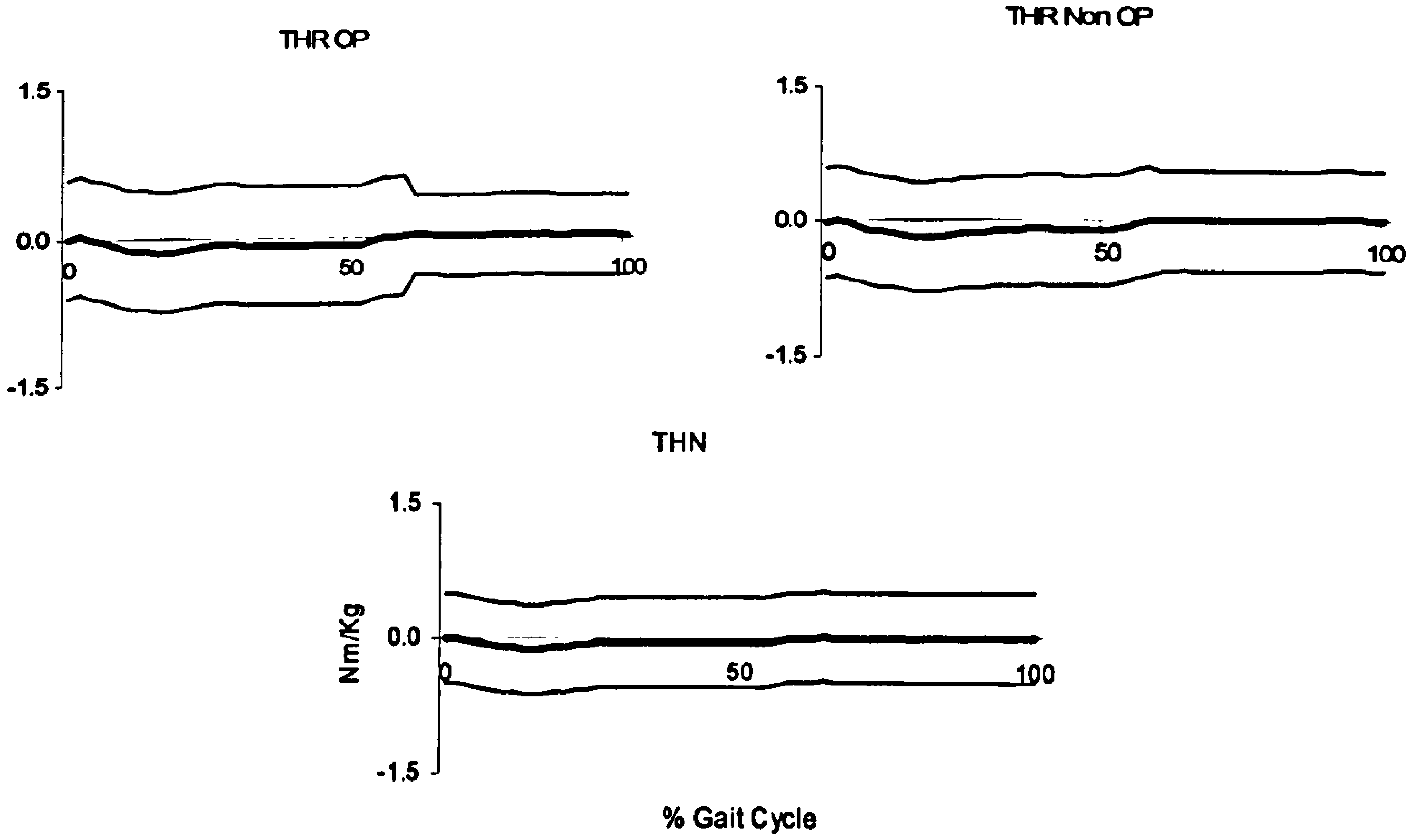


Figure 8.51 Horizontal Plane Hip moment patterns; average of three walking trials for one person with standard deviations, y axis (Nm/Kg), x axis % gait cycle

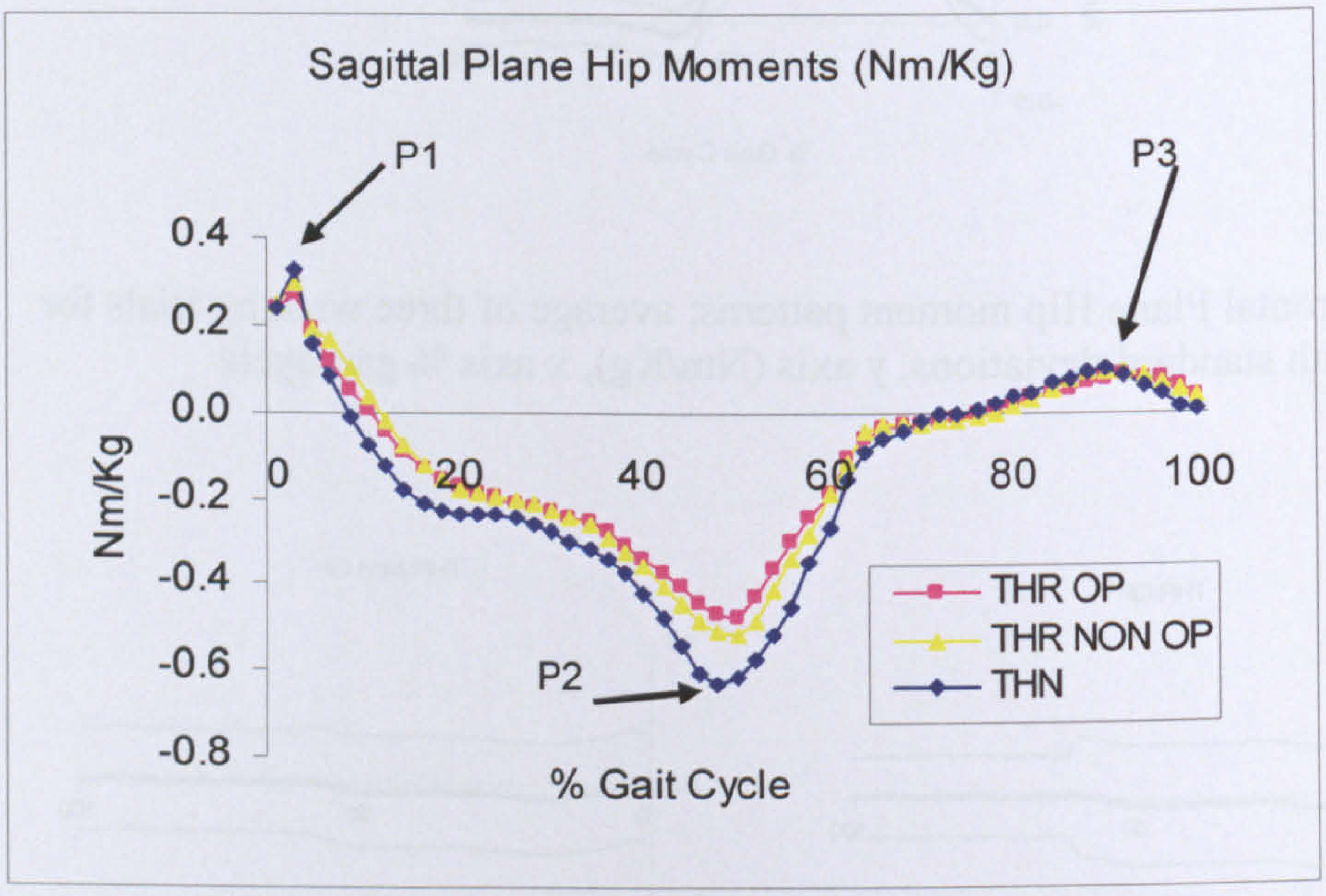


Figure 8.52 Sagittal Plane Hip Moments; averaged graph for each group, +ve = flexion internal moment.

8.6.3 Averaged hip joint moment data per group

Averaged internal hip joint moments per group in each plane can be seen in Figures 8.52 – 8.54 with time represented as 100% of the gait cycle on the abscissa axis and joint moments Nm/Kg on the ordinate axis. Minimum and maximum values from the averaged internal moment curves through the gait cycle for all data are given in Table 8.6.

Table 8.6 Minimum and maximum peak values from averaged internal hip moment data curves in the sagittal, frontal and horizontal planes for each of the groups.

	Peak moments	THR op	THR non op	THN
Sagittal	extension	-0.48	-0.52	-0.63
	flexion	0.27	0.29	0.32
Frontal	adduction	-0.03	-0.04	-0.06
	abduction	0.45	0.43	0.39
Horizontal	lateral rotation	-0.14	-0.13	-0.13
	medial rotation	0.01	0.01	0.02
All data measured in Nm/Kg				

The patterns of sagittal plane moments for all three groups (Figure 8.52) are very similar and there appears to be minimal difference between them. There is a flexion moment at initial contact and loading response (P1, Figure 8.52) and then the moment changes to extension at the end of loading response. Peak internal extension moment occurs at 50% of the gait cycle, start of terminal stance, for each of the groups (P2, Figure 8.52). This is the maximum moment at the hip joint through the gait cycle. By 76% of the gait cycle, start of initial swing, the extension moment reduced and a small flexion moment occurs and creates a second flexion peak moment at 92% of the gait cycle (P3, Figure 8.52). The THN pattern has the largest peak extension and flexion moments, whilst the THR op has the lowest peak

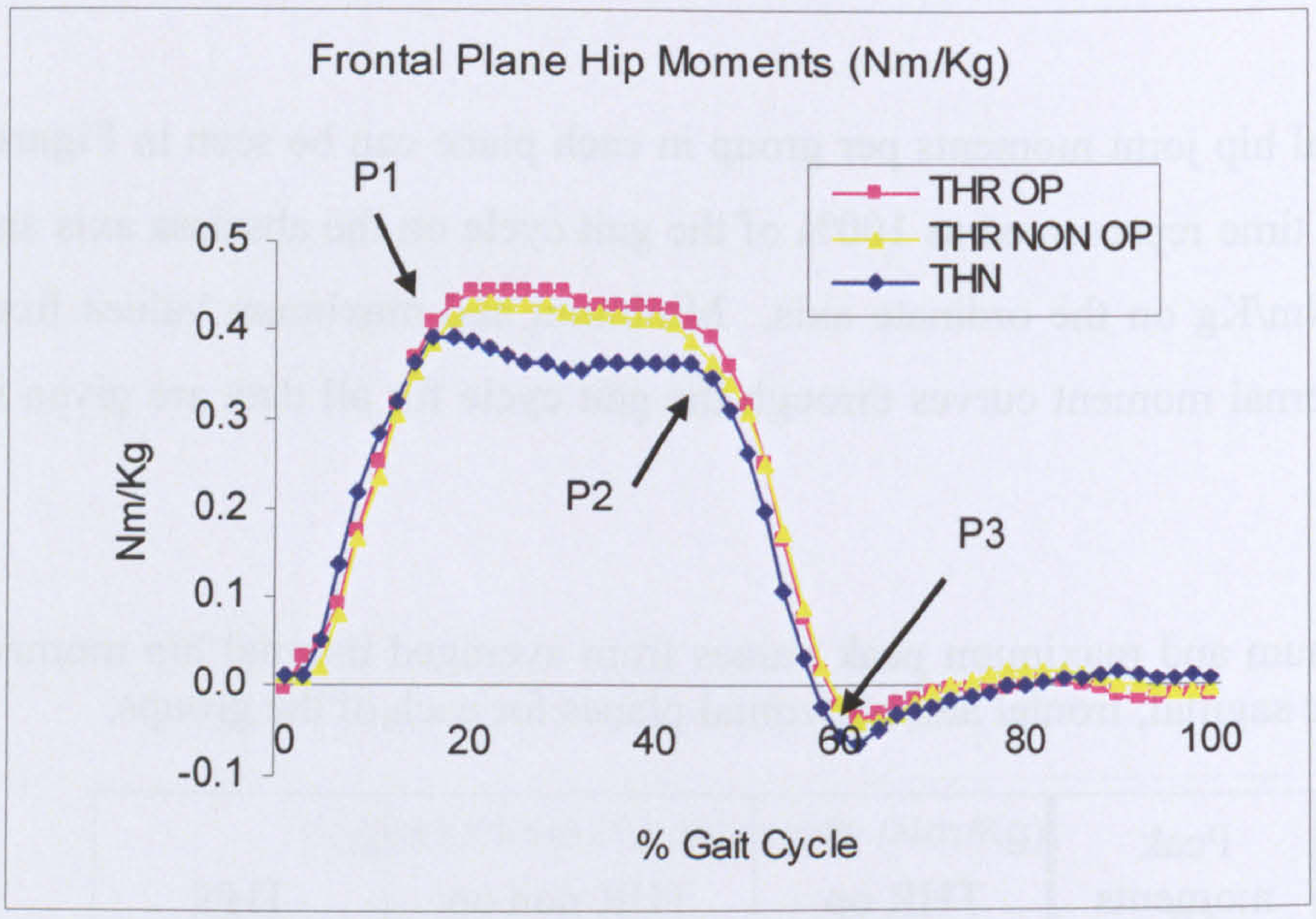


Figure 8.53 Frontal Plane Hip Moments; averaged graph for each group
+ve = abduction internal hip moment

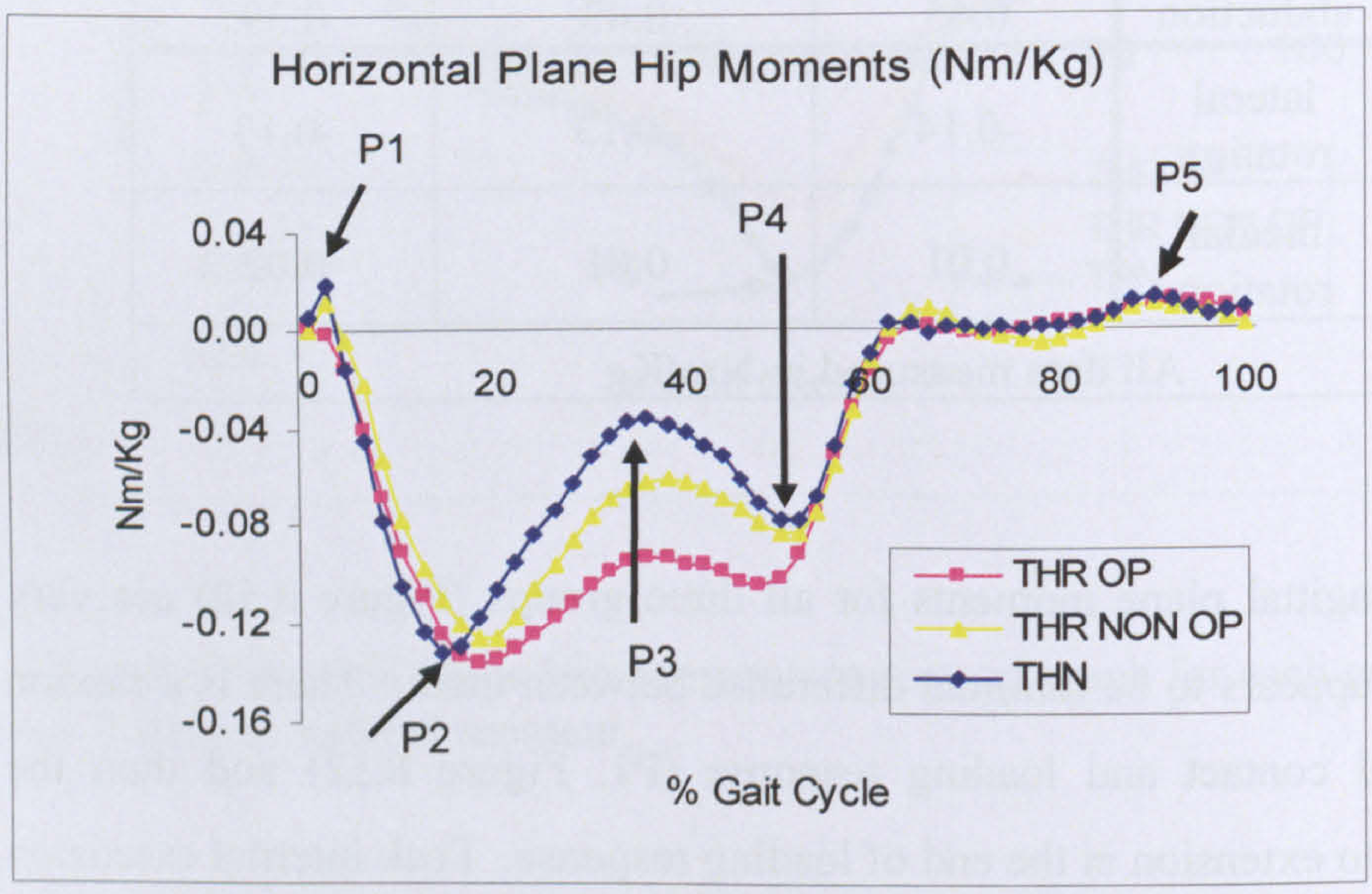


Figure 8.54 Horizontal Plane Hip Moments; averaged graph for each group
+ve = medial rotation internal hip moment

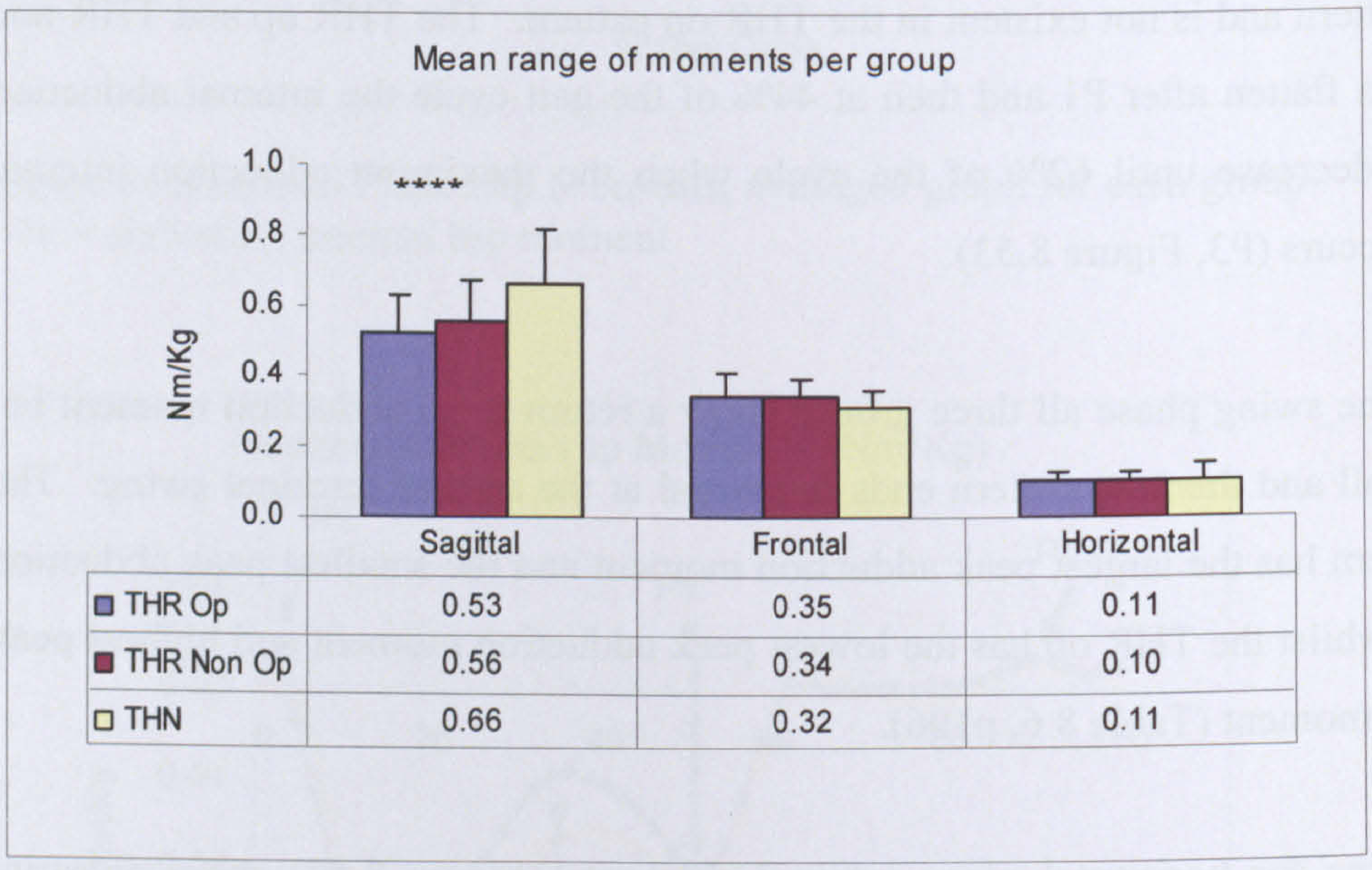
extension and flexion moments (Table 8.6). Peak flexion moments occur at P1 (Figure 8.52) for the THR non op and the THN groups but at P3 (Figure 8.52) for the THR op group.

Frontal plane internal moment patterns (Figure 8.53) show a slow rise in abduction moment from initial contact for all groups, with peak moment occurring at 18% of the gait cycle for the THN group, 22% for the THR non op group and 28% (P1, Figure 8.53) for the THR op group. The internal abduction moment then reduces in magnitude, with the THN pattern showing a second peak abduction moment at 42% of the gait cycle (P2, Figure 8.53). The second peak is less pronounced in the THR non op pattern and is not existent in the THR op pattern. The THR op and THR non op patterns flatten after P1 and then at 44% of the gait cycle the internal abduction moments decrease until 62% of the cycle when the maximum adduction internal moment occurs (P3, Figure 8.53).

Through the swing phase all three groups show a return to an abduction moment but this is small and then the pattern ends in neutral at the start of terminal swing. The THN pattern has the largest peak adduction moment and the smallest peak abduction moment, whilst the THR op has the lowest peak adduction moment and highest peak abduction moment (Table 8.6, p196).

The patterns for horizontal plane internal moments (Figure 8.54) show disparity through the stance phases of the gait cycle, but this is not present through swing. At initial contact there is a small medial rotation moment (P1, Figure 8.54), which quickly changes to a lateral rotation moment. Peak lateral rotation moment occurs at 14% of the gait cycle for the THN group and 18% of the cycle for the THR op and non op groups (P2, Figure 8.54). After peak lateral rotation there is a sharp change towards a medial rotation moment which is greater for the THN group than either of the THR groups (P3, Figure 8.54). The pattern is smoother for the THR op group.

A second peak lateral rotation moment occurs at 48-50% of the gait cycle for all groups with the THN having the smallest magnitude and the THR op group the



	Sagittal	Frontal	Horizontal
🟦 THR Op	0.53	0.35	0.11
🟥 THR Non Op	0.56	0.34	0.10
🟨 THN	0.66	0.32	0.11

Figure 8.55 Mean range of hip moments; averaged graph for each group, **** p=0.0007

largest (P4, Figure 8.54). Again the pattern changes towards a medial rotation moment with a second peak medial rotation moment at 64 -66% of the gait cycle. The pattern smoothes to neutral for all groups through the initial swing phase but there is a final medial rotation moment through terminal swing (P5, Figure 8.54). The THN pattern has the largest peak medial rotation moment and the smallest peak lateral rotation moment, whilst the THR op has the lowest peak medial rotation moment and highest peak lateral rotation moment (Table 8.6, p197).

Statistical comparisons of peak moment and ranges of moments for all planes will be presented in section 8.6.4.

8.6.4 Mean hip moment data

To assess the statistical variance in the data sets between groups the mean range of hip moments from each person the data was tested in three ways: average range of hip moments for sagittal, frontal and horizontal plane movement through the full gait cycle (Figure 8.55), peak hip moment through the gait cycle (Figure 8.56, p200A), mean hip moment at heel strike (Figure 8.57, p 201A) and mean hip moment at toe off (Figure 8.58, p202A).

8.6.4.1 Mean range of hip moments

The range of sagittal plane hip moments differed significantly (p=0.0007) between the three groups with the THN having the largest range and the THR op group the smallest (Figure 8.55). Post hoc t-test (Table 8.7, p200) identified this difference to be between the THR op and the THN group (p=0.0007) and between the THR non op and the THN groups (p=0.009).

There was no significant difference between the groups for either frontal or horizontal plane hip moments, however the THN group had a smaller range of frontal plane moments and the largest range for horizontal plane but the differences were negligible (Figure 8.55). The THR op group had the opposite results; the largest range for frontal plane moments and the smallest for horizontal.

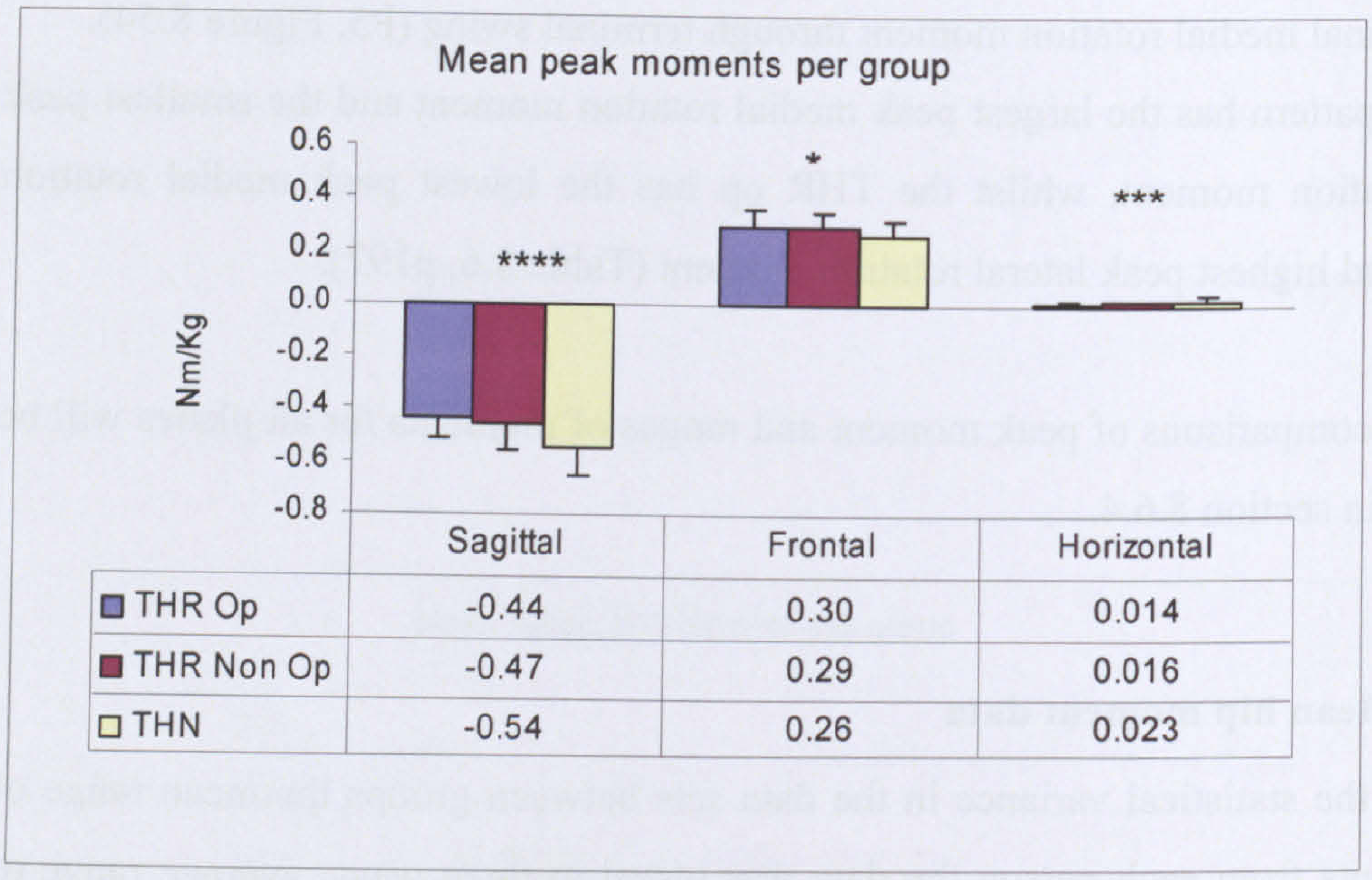


Figure 8.56 Peak hip moments (Nm/Kg); averaged graph for each group, * p = 0.032, *** p=0.008, ****p=0.0006

8.6.4.2 Mean peak hip moments

Peak hip moments were assessed as the largest moment occurring during the gait cycle in each of the three planes. In the sagittal plane this was extension, in the frontal abduction and the horizontal medial rotation. The differences between the groups were significant for all planes of moments using one way ANOVA (Figure 8.56), with the greatest difference in the sagittal plane (p=0.006), then the horizontal plane (p=0.008) and then the frontal plane (p=0.032).

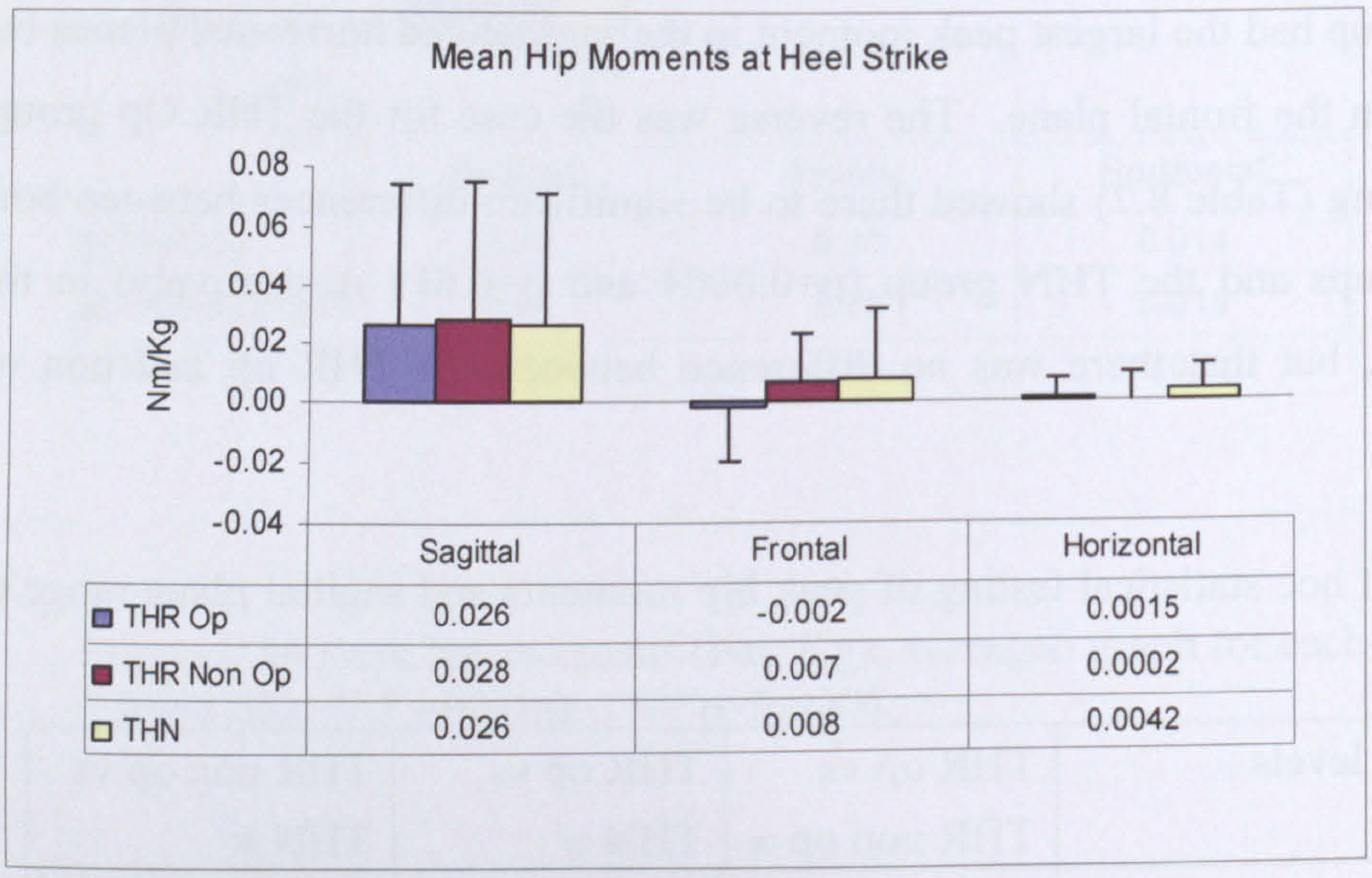
The THN group had the largest peak moment in the sagittal and horizontal planes but the smallest in the frontal plane. The reverse was the case for the THR Op group. Post hoc testing (Table 8.7) showed there to be significant differences between both the THR groups and the THN group (p=0.0004 and p=0.011 respectively) in the sagittal plane, but that there was no difference between the THR op and non op groups.

Table 8.7 Post hoc statistical testing of peak hip moments and sagittal plane range of moments.

Significance levels		THR op vs THR non op ≈	THR op vs THN ≡	THR non op vs THN ≡
Sagittal	Range	NS	0.0007	0.009
	- ve Peak	NS	0.0004	0.011
Frontal	+ ve Peak	NS	0.015	0.033
Horizontal	+ ve Peak	NS	0.008	0.039

Key:
THR op:- Operated side of the THR group
THR non op:- Non operated side of the THR group
THN:- control group (R& L data combined)
≈ tested by a paired t-test, ≡ tested by a non paired t-test
-ve = extension peak
NS:- Not significant
Significance < 0.017 with Bonferroni correction

In the frontal plane the THR op group had the largest peak moments and the THN group the smallest, whilst in the horizontal plane the THR op group had the smallest peak values and the THN the largest (Figure 8.56). Post hoc significant differences were found between the THR groups and the THN group in both the frontal and



	Sagittal	Frontal	Horizontal
🟦 THR Op	0.026	-0.002	0.0015
🟥 THR Non Op	0.028	0.007	0.0002
🟨 THN	0.026	0.008	0.0042

Figure 8.57 Hip moments at Heel Strike; averaged graph for each group, no statistical difference

horizontal planes (Table 8.7), however with Bonferroni correction the significance level reduces to $p<0.017$, resulting in the differences between the THR non op and THN group being non significant. Significant differences were found between the THR op and THN group in both the frontal and horizontal planes. There was no significant difference between the THR op and non op groups for either plane.

8.6.4.3 Mean hip moments at heel strike

The mean hip moments at heel strike are similar (Figure 8.57) and there were no significant differences between the groups for any plane when tested by one way ANOVA. The mean values for the moment at heel strike are small and the standard deviations for all values are large in all planes, showing the variability of this measure. The largest variability in the standard deviations is in the sagittal plane.

The mean moment in the frontal plane for the THR op group is in adduction whilst those for the THR non op and THN groups are in abduction. The THN group have the largest frontal plane moments at heel strike and the THR op group the smallest. All moments in the horizontal plane are small but the THR non op group has the smallest moment and the THN group the largest.

8.6.5 Hip Moment – Angle Comparisons

Comparison of hip moment data is difficult due to the different units of measurement and although traditionally moment time graphs are recognisable they do not offer the full picture of the 3-dimensional story from kinetic and kinematic research. To try to display the kinetic results in a meaningful way, mean hip moment data was correlated with mean hip angle data through the gait cycle and present in a similar format to the angle-angle diagrams in section 8.5.

The moment–angle graph gives information about hip moments, hip range, the interaction of these and of the timing of the interaction, as each of the data points represents 2% of the gait cycle the closer the data points are together the faster the movement. Figure 8.58 (p202A) presents the moment–angle graphs for each group

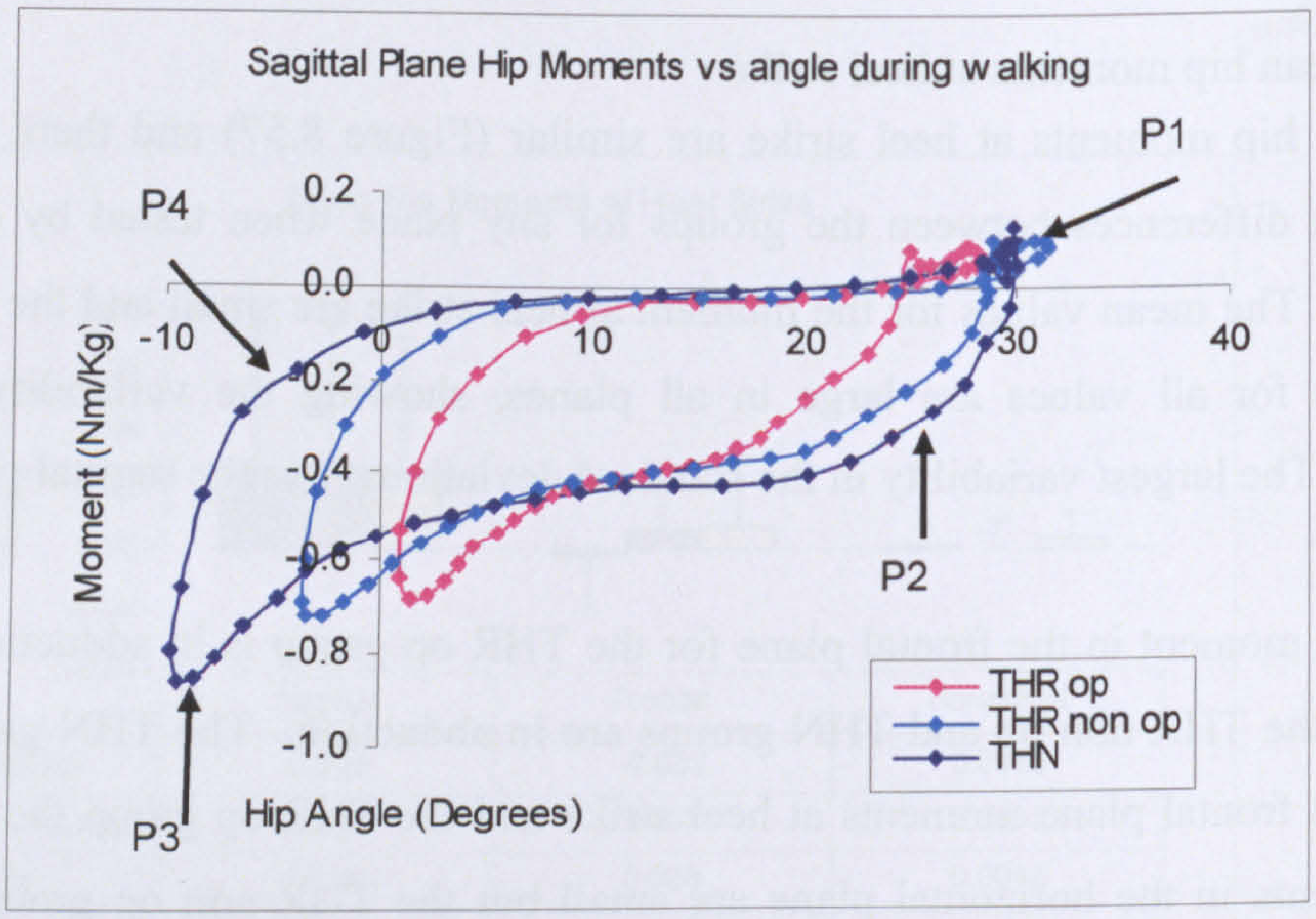


Figure 8.58 Moment-Angle graphs in the sagittal plane

for sagittal plane only, as the data for the frontal and horizontal plane moments are more diverse, difficult to compute and more data is needed to make these graphs understandable.

In the sagittal plane the reduced hip range is evident from the moment –angle graph with a double loop showing for all three groups. The hip starts in a short flexor moment and continues clockwise into a much bigger extensor moment which continues to run clockwise. At the end of the gait cycle there is an anti-clockwise loop when the hip returns to the flexor moment during the last 24% of the gait cycle.

Bunching of the data point at the start of the gait cycle (P1) indicates a fast transition with small changes in movement and in moment during the flexor phase. The slower extensor moment (P2) predominates through the gait cycle before returning to a flexor moment near the end of the cycle. The pattern for the THN participants is muddled for the flexor phase but is clearer for the THR op and non op groups. All three groups follow very similar patterns in the sagittal plane with larger extensor than flexor moments and range of motion. The peak of extension moment and range falls at 50% of the gait cycle for each of the groups (P3) which is approximately at the start of push off into pre-swing when the body is being propelled forward. At the start of the swing phase (61.09%) the THN the moment reducing to neutral and then back to a flexor moment at mid swing (P4).

8.6.6 Summary of Hip Moment results

Summary of Hip Moment Results

- Peak and range of internal hip moments through the gait cycle were calculated along with the mean hip moments at heel strike and toe off. Moments were normalised by body mass (Nm/Kg).

- Statistically significant differences were identified in the range of hip moments in the sagittal plane between the THR groups and the THN group, p=0.0007 and 0.009, respectively. No statistical differences were found in any other plane.

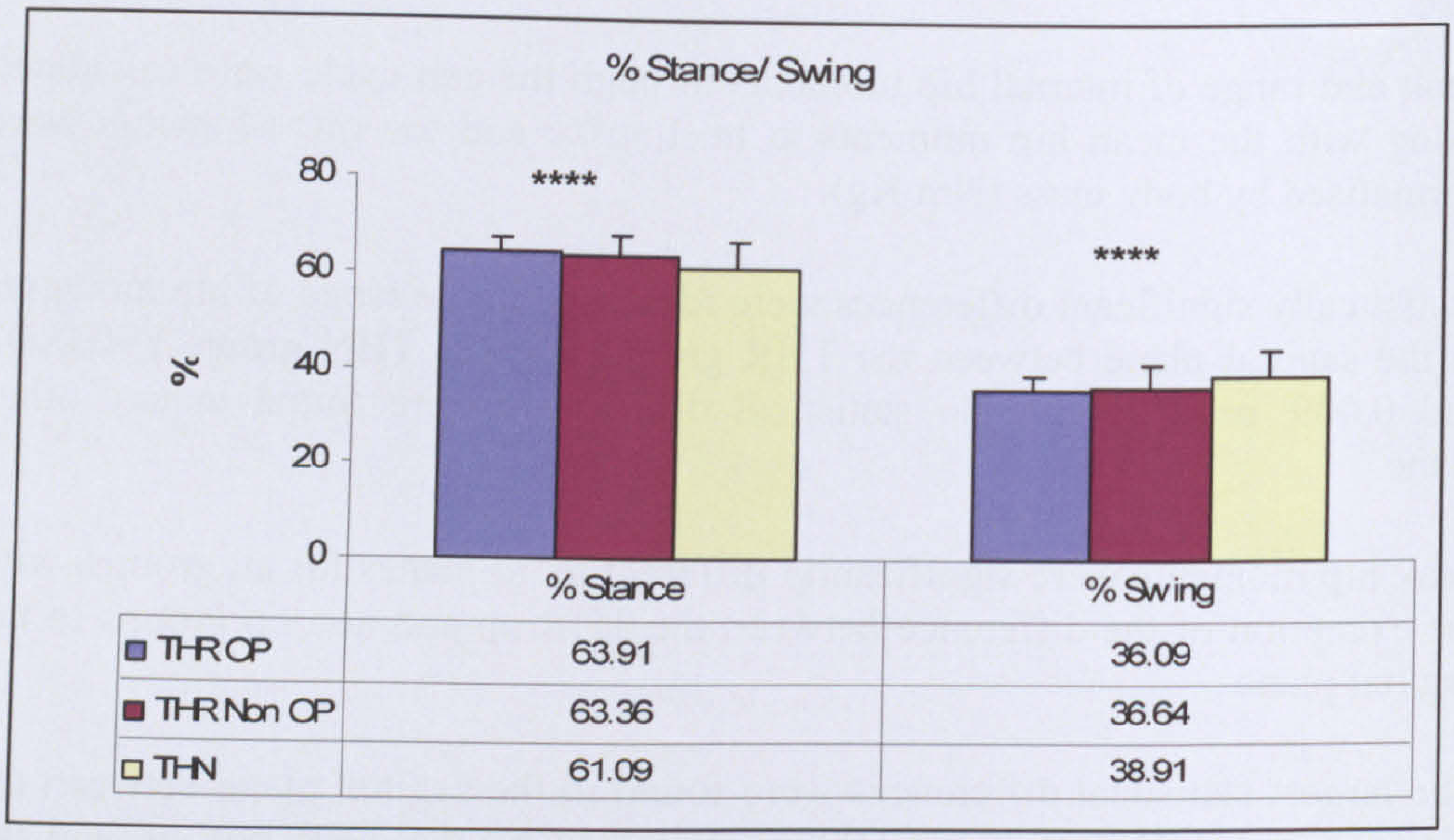
- Peak hip moments were significantly different in all planes for all groups, with the exception of the difference between the THR op and non op groups in the sagittal plane.

- The largest statistical differences were found in the sagittal plane between the THR op and THN group (p=0.0004), followed by the THR non op and the THN group (p=0.011).

- Frontal plane peak moments were significantly different between all the groups (THR op vs THR non op,p= 0.02), (THR op Vs THN p=0.015), (THR non op vs THN p=0.008). With Bonferroni correction the THR op vs non op differences did not reach the significant level ($p<0.017$).

- Horizontal plane peak moments were not significantly different between all the groups as with Bonferroni correction the significant level is $p<0.017$: (THR op vs THR non op, p= 0.023), (THR op vs THN, p=0.03), (THR non op vs THN, p=0.039)

- There was no statistical difference between the mean hip moments at heel strike and at toe off between any of the groups for any of the planes. The standard deviations for these mean values were large.



	% Stance	% Swing
■ THR OP	63.91	36.09
■ THR Non OP	63.36	36.64
□ THN	61.09	38.91

Figure 8.59 Mean percentage stance and swing values for each data set, **** = $p < 0.0001$

8.7 TIMING OF MOVEMENT

8.7.1 Velocity

Mean walking velocity over the 10 metre walkway for participants in each group was 1.10 ±0.13 m/s, 1.12±0.14 m/s and 1.22±0.07 m/s for the THR op, THR non op and THN groups, respectively. No significant difference was found between these values.

8.7.2 Mean stance and swing percentages of gait cycle

Mean percentages of the gait cycle were calculated for stance and swing phases, mean group data can be found in Appendix W. The THN group had a significantly shorter stance (61.09%) and longer swing phase (38.91%) when compared to either the THR op or THR Non op values($p<0.0001$). The THR op group had the largest values for stance (63.93%) and the smallest swing phase values (36.09%) (Figure 8.59). Post hoc testing identified that the THR op and THR Non op values were not significantly different therefore these values were combined to test all THR values against the THN values. The mean and standard deviations for the combined data in stance (63.76±3.48%) and swing (36.24±3.48%) were significantly different to the THN values (Table 8.8).

Table 8.8 Post hoc Statistical analysis of percentage stance and swing times student t-test results

	THR op vs THR Non op	THR vs THN
p values	Paired t-test	Unpaired t-test
Stance Phase	0.39	0.0000007
Swing Phase	0.39	0.0000007

9.0 SUMMARY OVERVIEW OF ALL FINDINGS

This chapter can be seen as an overall executive summary of the findings presented in the two previous chapters. It also serves to introduce discussion of the biomechanical data in chapter 10 – the final chapter in this thesis investigating the patterns of hip and lumbar spine movements in patients two years after total hip replacement (THR), compared to those of a normal group of healthy individuals (THN). Data was collected and analysed from 24 patients in each group – for the THR group, data for both the operated (THR op) and non-operated sides (THR nonop) was investigated – for the THN data for the right and left sides was averaged and then analysed. Both groups were matched by age and gender and all were physically active. Overall the ratio of male to female participants was 1:2.6 with 3 more males (5:8) in the THN group.

Demographic data: When tested by independent t-test, there was no difference between the two groups in respect of age, weight or height. Using two-way analysis of variance, post hoc analysis showed that the male participants in each group were significantly taller and heavier than their female counterparts. Average time from surgery was 27.7 months and the majority (n=15) of THR surgery was to the right leg.

Function and leisure: Eight people in the THR group used a walking aid for reassurance and to assist outside walking, four had minimal hip pain when walking and 15 people in this group had some degree of lumbar pain that interfered with their daily routine. None of THN group used a walking stick and only one person complained of minimal back pain. While all of the THN group participated in at least one active leisure pursuit, those in the THR group had more passive leisure pastimes.

Passive Physiological movement

Hip: In lying, the THR groups had significantly reduced movement in the sagittal (flexion, extension), frontal (abduction, adduction) and horizontal (external and internal rotation) planes compared to the THN group. Comparison within the THR group showed that the non-operated hips (THR nonop) had significantly more flexion, abduction and external rotation in 70° of flexion than the operated hips (THR op) but in respect of extension and internal rotation at 70° of flexion, the operated hips had marginally more movement.

Lumbar spine: In the sagittal plane in standing, the THR groups had significantly less lumbar flexion than the THN group and significantly more extension with a non-significant reduction in lumbar lordosis. In the frontal plane, both right and left lateral lumbar flexion was significantly reduced in the THR groups compared to the THN group.

Knee: the sagittal plane, there was no difference in knee extension between the two groups but the THR group had significantly less knee flexion than the THN group. There was no apparent difference in mean range of knee movement between the THR nonop and THR op groups.

Biomechanical data of gait

Range of movement

Biomechanical data was collected from walking test for both limbs from the participants in each group. Data for the THN group showed no statistical difference between the right and left side, so these were grouped together. Data from the THR group was examined for the operated side (THR op group) and the non operated side (THR non op group).

Hip: One-way analysis of variance showed that the dynamic range of movement in all 3 planes was significantly decreased for the THR op side when compared to both the THR nonop side and the THN group. Post-hoc analysis showed that significant differences occurred between the THR groups and the THN group for all three planes. The range of motion of the THR op and THR nonop sides only differed significantly in the sagittal plane. All three groups had a similar pattern of movement but the ranges at the extremes of the cycle differed. Significant differences in hip range were identified at initial contact (heel strike) and at transition from stance to swing (toe off) in the sagittal and frontal planes between the THR and THN groups and between the THR sides at sagittal plane heel strike.

Pelvis: Pelvic movement was considerably but not significantly reduced in the THR group in all three planes of movement in respect of range of movement and at heel strike and toe off. The THR non-op side was in more anterior tilt when compared to the THN group and had less movement in the frontal plane. In the horizontal plane, there was less rotation at heel strike but an increase in backward rotation at toe off.

Lumbar spine: Overall, it can be seen from the curve patterns (Figures 8.33-8.35) that the THR op side has an altered pattern of lumbar spine movement to that of the THN group in all three planes of movement. One way-analysis of variance together with post hoc testing showed a significant difference between THN and the THR op groups with the THN group having significantly less average range of motion in the sagittal plane. Similarly at toe off in the frontal plane, the average range of motion was significantly less for the two THR groups than for the THN group.

Interaction of movement:
Sagittal plane: Angle-angle diagrams analysing interactions of hip and pelvis respectively with movement of the lumbar spine confirm that overall less movement occurs in the THR groups associated with a difference in timing sequence when compared that of the THN group. These observations can be related to the significant differences in range of motion of the hip were found in this plane between the THN and both THR groups already noted. Differences in hip and pelvic interactions were not apparent.

Frontal plane: Patterns of movement in this plane for hip and lumbar spine, hip and pelvis and pelvis and lumbar spine are different for all three groups for both range and timing with the hip and pelvis interactions being smallest. The pelvic and lumbar spine interactions show four clear points of change and faster movement which not apparent in either THR group.

Horizontal plane: The pattern of movement of pelvic and lumbar spine interactions differs between groups. The THR groups show a setting pattern at heel strike and toe off – the start and end of single limb support. This pattern does not occur in the THN group.

Moments:

Hip: The range of sagittal hip moments was significantly greater in the THN group when compared to that of both THR op and THR nonop groups.

Peak moments: These were significantly different in all three planes for all three groups with the exception of differences in the sagittal plane between the THR nonop and THR op groups. The most marked differences in peak moments were in the sagittal plane between the THR op and THN groups, followed by that shown between the THR nonop and THN groups. Both frontal and horizontal plane peak moments were respectively significantly different (p ranging from 0.023-0.039) between all three groups although with the Bonferroni correction, these did not reach significance ($p<0.017$).

Walking velocity: Differences in walking velocities did not reach significance. But the THN group had a significantly shorter stance time than either of the two THR groups

10.0 DISCUSSION OF BIOMECHANICAL DATA

Kinematic and kinetic gait data from 48 participants was gathered and analysed. Because of difficulties with the original analysis software programme, the processing of the data was extracted. ASCII plug-in software for Vicon Workstation and the 'body-builder' software programme were written and the data was processed efficiently. Earlier in Chapter 5, the accuracy of the Kinemetrix motion analysis system has been presented both in terms of accuracy and reliability (see 5.4.2) and in terms of marker placement (see 5.4.3) establishing acceptably high levels of reliability with LSD of less than 5° for hip, pelvis and lumbar spine in all three planes of motion. The overall measurement error of the Kinemetrix was a mean of 1.29°.

As in previous chapters, data is presented by group; two groups for those 24 participants who had had a hip replacement 1) THR op - data from the operated side 2) THR non op - data from the non-operated side and 3) THN - averaged data from the right and left sided sides of 24 age matched normal participants who had not had a hip replacement. Data from hip, pelvis and lumbar spine was collected throughout the walking cycle. Comparisons were made between mean values of ranges of motion, peak mean hip moments and mean movement and hip moments at heel strike and toe off. Applying Bonferroni correction for repeated use of data to all post hoc testing, a significance level was set at $p<0.017$.

An overall summary of the results from the biomechanical data has been given in Chapter 9. From these findings several areas of particular interest have been selected. The plan in this final chapter is to discuss these areas in relation to other biomechanical findings and to the published literature.

Areas for discussion:

1. Range of movement: The significant differences in range of motion found in the hip and lumbar spine during gait in the THR and THN groups in both sagittal and frontal planes will be reviewed.

2. Angle-angle diagrams: The impact of these diagrams in demonstrating differences in pattern and timing otherwise described as the interaction of movement during walking between the hip and lumbar spine, lumbar spine and pelvis and pelvis and hip in all three groups will be discussed.

3. Peak moments: The significant differences identified in peak hip moments in the THR op and THN groups in both sagittal and frontal planes will be explored as will those of the THR nonop and THN peak moments in both planes.

10.1 RANGE OF MOVEMENT

For ease of discussion, the figures of the pattern of movement at the hip, pelvis and lumbar spine will be reviewed for each plane of motion for the respective THR op and THR non op groups and the THN group. As indicated in both Chapters 8 and 9, significant between group differences (p values ranging from 0 00001 - 0 004) in range of motion during normal relaxed walking were found in all three planes of movement at two years after surgery. Reminder copies of range of motion figures are given in Figure 10.1, p212A; 10.2, p220A and 10.3, p229A for ease.

10.1.1 Sagittal plane patterns of motion: hip, pelvis and lumbar spine

Overall sagittal plane motion between the groups showed a decrease in hip movement between the THR groups and the THN group, an increase in motion in lumbar spine motion of the THR groups compared to the THN group and no significant difference between any of the groups for pelvic motion.

It seems that after total hip replacement, as pain and loss of movement at the hip joint have been relieved, pelvic motion returns to a normal level. This suggests that there is a desire to return to a faster and more normal walking and possibly because the hip joint is not yet sufficiently strong and lacks the necessary control, the response is to increase spinal movement.

Earlier work by Rowe at al (1989) established that individuals, who had regained 90% of their walking speed by 12 months post surgery, increased their step length during the first two months and cadence within two to six months. But average hip motion in the sagittal plane had only increased by 54% at 12 months and was significantly less ($p=0.05$) than that of the aged matched normal subjects. Rowe and his colleagues suggested that to achieve the speed changes without full recovery of hip motion that either lumbar spine or pelvic compensatory motion had increased cadence.

Given that at two years post surgery, the mean walking velocity in the present THR groups (THR op 1.10m/s, THR non op 1.12m/s) had returned to an acceptable level compared to the current THN (1.22m/s) group and to the published literature (1.25 m/s Crosbie et al 1997b, 1.3±0.19 m/s, Kababa et al 1990), it is likely that 'lumbar-pelvic' compensation becomes the 'normal' pattern following THR.

10.1.1.1 Hip

The mean sagittal range of hip motion during walking was respectively 29.0°, 36.31° and 42.25° for the THR op and non op sides and THN group. These differences were significant when comparing overall range between the groups; post hoc testing identified significant between groups differences for the THR op and non op groups, the THR op and THN groups and the THR and THN groups. The mean range of 42.25° of sagittal plane movement and preferred walking velocity of 1.22±0.07m/s for the present THN group (mean age 73.4±4.05 years) compares with that of the group of seniors (age 50-82 years) studied by Crosbie et al (1997b). They were found to have a mean sagittal range

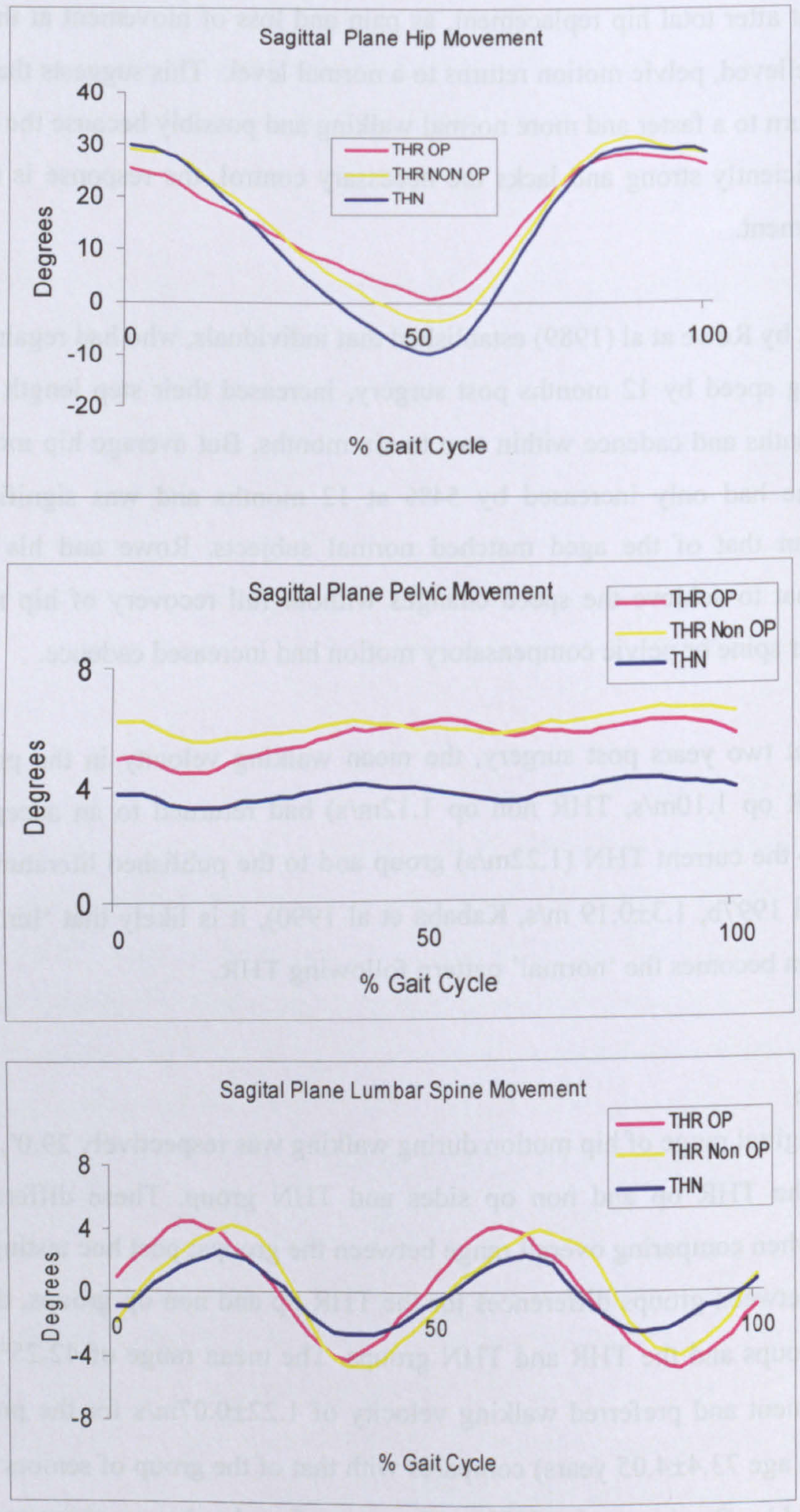


Figure 10.1 Sagittal plane movements of the hip, pelvis and lumbar spine

of hip motion of 43.5±5° at their preferred walking speed of 1.25m/s. In a group of 40 younger (aged 20-40 years) healthy participants, Kadaba et al (1990) and Winter (1983) found similar sagittal ranges of hip movement of 43° in respective groups of younger healthy adults, aged 20 -40 years.

Sagittal plane hip movement for all groups followed the well–established pattern of movement during walking (Whittle 1996a; Perry, 1992; Kadaba et al, 1989, 1990; Winter, 1987, 1984, 1983 & Table 4.10, 4.11). The THR op patterns for all three planes are similar to those reported by Perron et al (2000) who studied 18 subjects 12 months after THR surgery. The patterns of movement for the THR groups differed from those of the THN group with reduced hip flexion and extension on the operated side and reduced hip extension on the non operated side. In the THR op group peak extension occurred approximately 4% later in the gait cycle replicating the findings of Perron and his colleagues (2000) who also showed that their THR group had delayed peak extension.

The mean value of range of motion for the THR op group of 29±7.74° was similar to the mean range of motion (27.18±8.37°) found by Stanic et al (1993) 12 months post surgery and to the mean value of 25° established by Perron at al (2000). Both groups of researchers used similar motion analysis systems to the current study. Long et al (1993) reported a mean sagittal plane movement of 37° one year after surgery with an uncemented THR in 18 patients (mean age 55 years) but their patients were younger and their pre operative sagittal range of motion was 27°. They reported that the non operated side had a range of motion of 41°, gaining 4°of motion pre to post surgery, with the range being larger than the present study (36.31±8.99°). Hurwitz et al (1993) reported that THR participants showed a significant difference between the operated, non operated and healthy hip range of motion for the affected side but not for the unaffected side. More importantly the shape of the hip pattern for the post operative hip and the unaffected hip was much "bumpier" that that of the healthy gait and they suggest that this is either a learnt response from the pre-operative stage or an attempt to reduce the rotational forces on the hip replacement. The time since surgery has not been reported for this study. Hurwtiz et al (1992) also suggested from their research on following un-cemented total hip replacement that a reduction in active hip range of motion during gait after total hip replacement was a modifying response to reduce torsional "micromotion" at the hip replacement attachment. There is every reason that this should occur in participants with cemented hip arthroplasties to preserve the longevity of the joint and reduce pain.

Aminian et al (2004) compared hip data measured by a kinematic sensor to that gathered by the Elite motion analysis system and showed a difference of 1.7±3.5°. In a preliminary comparison of Biometric twin axis strain gauge electrogoniometers (BEG) with the present Kinemetrix system, this present study showed (Section 4.2.1.5, Table 4.5) for measurements of movement of the lumbar spine was comparable using both systems, the BEG system was more variable in its measurement of the range of motion of the hip.

Using a twin axis electrogoniometer over tubigrip tights, which may have restricted thigh movement, Rowe et al (1989) measured 16.94° of hip flexion/extension range following surgery, while using goniometry Stauffer et al (1974) and Olsson et al (1986) recorded mean ranges of 32.8°and 38° respectively. Aminian et al (2004) using kinematic sensors worn over trousers found an overall mean range of 38±4° in 8 THR patients 18 -36 months after surgery but may have recorded 'trouser' as well as thigh movement.

These results suggest that although there was a slight improvement in the sagittal plane of movement of flexion and extension of the hip joint at two years after surgery when compared to the values established at 12 months using comparable motion analysis systems (Stanic et al, 1993, Perron et al, 2000), the movement does not reach that of the non-operated side.

10.1.1.2 Pelvis

Figure 10.1 shows that the sagittal plane movements of the pelvis are small compared with those of the hip and lumbar spine and that for both THR and THN groups, pelvic motion remains in forward tilt (Horizontal plane motion) throughout the gait cycle. There were no significant differences in the mean range of motion of the three groups with the THR op group having a mean range of 3.92±1.19° and the THR nonop and the THN groups having mean ranges of 3.55±0.93° and 3.87±1.25° respectively. Figures 8.20 and 10.1 show that the THR op group has the largest amount of forward tilt and that anterior tilt (Sagittal plane) increases in the THR nonop group between mid and terminal stance. Whereas apart from being in a greater degree of forward tilt, the THR op and THN patterns of motion are comparable throughout the gait cycle.

Earlier results from Murray and his colleagues (1969) using photography and single markers in a group of men aged from 74 -80 years recorded a range of pelvic sagittal movement (9°) during walking. More recent results from published literature (see table 4.7 p 89A) on normal sagittal pelvic motion with age are comparable to the findings of the THN group in the present study. Kadaba et al (1990, 1989) and Whittle & Levine (1999) using rig markers identified respective small sagittal plane ranges around a mean position of 6°, 15° and 11°. Using skin markers rather than rig markers, Crosbie at al (1997a) found a different pelvic movement pattern in that the pelvis titled backwards at heel strike (2°) and then forwards during the first 10% of the gait cycle. The forward tilt was less than 1° giving an overall mean motion in the sagittal plane of 3±1.5°. These differences in the observed patterns may have resulted from skin movement under the four pelvic markers reproducing a coupling motion from 3-dimensional movement of the pelvis and lumbar spine. In this present study, a 3-point plate system was devised with only one contact point directly over the most stable part of the pelvis (S_2) and this was shown to have good test-retest reliability with a difference of a mean of less than 2.5°.

Apart from a recent report by Bennett et al (2006), no other published data has been found on pelvic motion following hip replacement. Bennett and his colleagues assessed eight patients aged 60.8±5.8 years 6 weeks after hip replacement surgery and found a range of pelvic motion of 5.9°, which is larger than that of the present study (3.92±1.19°). The pattern of increased sagittal pelvic movement identified by Bennett et al, is similar to that found by Thurston 1985 who examined the gait of patients with primary unilateral OA, where increased sagittal plane pelvic motion correlated with those with greatest hip pathology. At 6 weeks post surgery, Bennett et al (2006) may have been recording a pre surgical learnt pattern which was still present immediately post but which had diminished by 2 year post surgery as reported in the present study.

10.1.1.3 Lumbar spine

The pattern of movement from the sagittal plane lumbar data during gait demonstrated a reciprocal pattern of movement between flexion and extension with two phases of each through one gait cycle. The pattern of THN sagittal plane movement during the gait cycle replicates the general pattern found by Whittle & Levine (1999), Crosbie et al (1997) and Thurston & Harris (1983). The pattern shows two peaks of flexion at midstance and the start of pre swing, with the extension patterns at terminal stance and mid swing. Although similar to that found by Thurston & Harris (1983), these authors showed a notch on the curve from the first and second extension peaks to the flexion peaks at approximately 30 and 80% of the gait cycle in single limb support with the opposing leg moving past the other, the significance of this will be discussed later. Whittle & Levine (1999) identify a double flexion pattern through the stance phase which changes to an extension pattern at the end of terminal stance and decreases through the swing phase but does not go into flexion. There is a final dip into extension in the terminal swing phase.

Rowe & White (1996) report that it is more difficult to reproduce sagittal spinal movement than any of the other lumbar spine movements and this may explain the altered pattern between the three main published reports. Although not discussed in the original paper, the author suggests that the difficulty in reproducing sagittal spine movement is due to a larger degree of movement in this plane during walking. This is supported by Whittle & Levine (1999) who found that lumbar sagittal movement is highly individualistic but very repeatable within a person. Flexion and extension lumbar spine movement modifies to help compensate for altered movement elsewhere in the lower limb chain especially at the hip (Murray et al, 1971) and therefore any variance in limb movement would be represented by change in sagittal spinal motion. Group variance can be clearly seen in lumbar spine motion through the gait cycle for the present study (Appendix X).

Both Crosbie et al (1997a) and Thurston & Harris (1983) studied older participants, with Crosbie et al (1997b) reporting movement patterns for both a young and an older group. The variance between sagittal plane motion in the younger and older participants is clearly seen in Figure 3B (p18) of their paper. The younger females had a different pattern of lumbar spine rotation to the other groups and that may have influenced their mean data with the older participants having a pattern of movement similar to the current study see Crosbie et al (1997b) where they observed that significant differences in sagittal lumbar movement with speed may have influence the differences between the age groups. The mean preferred walking speed in older participants was 1.25±0.2m/s was comparable to the current study (1.22±0.7 m/s).

Figure 8.33 reproduced in Figure 10.1, shows that the pattern of sagittal lumbar spine motion for the THR non op group followed that of the THN group with the peaks occurring at the same time periods except for the 2nd extension peak which occurs at 6% of the gait cycle. The magnitude of the peaks is greater for the THR non op groups. The THR op pattern replicates the two peak pattern of flexion and extension but both peaks occur earlier in the cycle by between 6 - 8%. The first extension peak falls at the same time as the THR non op and the THN group but the second extension peak is 6% after that of the THN but at the same time as the THR non op group. Again the peaks of flexion and extension are larger than those of the THN group.

There is no literature to support the lumbar spine patterns from participants with total hip replacement as lumbar spine movement has not been investigated previously in this population. This present study shows that overall lumbar spine range of motion was significantly greater in the THR op group (9.06°) than in either the THR nonop (8.75°) or the THN (5.19°) and post hoc testing showed significant differences between the THR op group and the THN group but with Bonferroni correction not between the THR non op and THN groups. But there were no between group differences (THR op 3.92°, THR nonop 3.55°, THN 3.87°) in pelvic movement [see earlier discussion p215], indicating that at two years post surgery, in the sagittal plane, there was an interaction between the decrease in movement of the hip in both operated and non-operated hip joints and the increase in movement of the lumbar spine.

Range of sagittal lumbar spine motion varies from 3.5-6.21° in equivalent studies of healthy adults (Whittle & Levine (1999), Callaghan et al (1999), Crosbie et al, (1997a), Taylor et al (1996), Thurston & Harris (1983)). The data from the current study (5.2°±1.68) falls within this limit and is comparable with the results (5.2°±1.2) of Thurston & Harris (1983). There was a marked age difference between the two studies (73.04 & 32.3 years respectively) supporting the view of Crosbie et al (1997b) that age does effect lumbar spinal movement although some variation appears to be associated with the method of assessment .

In contrast to the range of motion of the THN group, the THR group's movement in the sagittal plane was 9.06 ± 2.08° and 8.75 ± 3.77° for the op and nonop sides respectively. Previous work by Thurston (1985) assessing pelvic and lumbar spinal movement in 19 subjects with OA hips with that of 10 aged matched non OA participants found no difference in sagittal plane lumbar spine motion (5.2± 2.2° and 5.2±1.07° respectively) but differences in pelvic movement. As discussed in the previous section the post op difference at two years do not follow this pattern. Thurston & Harris (1983) in an earlier study of younger people showed marked variation in lumbar spine movement in the sagittal plane suggesting that in the young, sagittal plane lumbar spine motion is optional depending on individual characteristics. In contrast, in the present study sagittal lumbar spine motion appears to be required in order to achieve increased ranges of motion and faster walking as suggested by Crosbie et al (1997b).

Shimada (19960 suggested that increased pelvic tilt and lumbar lordosis would compensate for hip flexion contractures of less than 15° (loss of hip extension). Alternatively Thurston (1985) suggests that there would be a compensatory increase in pelvic movement but a reduction in movement in the lumbar spine and further that this reduction could be used as a measure of severity of hip limitation. The results from this present study indicate that the pelvis does not play an important role in compensating for diminished sagittal plane hip motion and it appears that the lumbar spine may play this role. Peak mean extension during the gait cycle was 0.96° (Figure 8.7, p169A) on the THR operated side, with the deficit between this and the THN group being 9°, this may be too small an amount to introduce pelvic compensation when the lumbar spine can more effectively make up for the loss of hip extension.

Sagittal plane motion at the hip, lumbar spine and pelvis show clear differences in both magnitude and pattern between the three groups. In the THR op group, there is a concomitant decrease in hip movement, increase in lumbar spine movement and no significant change in pelvic motion when compared to the THN group. The THR non op group show similar trends. These results differ from those seen in people with OA hips. It is suggested that sagittal plane pelvis and lumbar spine patterns and ranges change pre to post operation with the lumbar spine playing a greater role in compensatory sagittal movement after surgery (Hurwitz et al, 1997) when the hip has reduced movement to that observed in a healthy control population. This author suggest that when there is a large degree of fixed flexion or loss of extension the pelvis interacts to accommodate for this loss as there is a greater ability and variability of movement. If hip extension loss is smaller then the lumbar spine can accommodate this loss more easily without involving the pelvis.

10.1.2 Frontal plane patterns of motion: hip, lumbar spine and pelvis

Patterns of movement (Figure 10.2) in the frontal plane for the THN group are again representative of some of the findings in the literature in particular Rose & Gamble (2006) and Kadaba et al (1990 & 1989) for all movements, and Crosbie et al (1997a) and Thurston & Harris (1983) for the lumbar spine pattern. Literature searching has not identified any corresponding literature for populations with a total hip replacement except for that by Perron et al (2002) who looked at lateral movement of the whole trunk.

Overall, frontal plane hip, lumbar spine and pelvic motion between the groups showed a significant decrease in excursion at the hip joint with the THR op hip remaining in adduction throughout the cycle. Pelvic movement was not different between the groups however lumbar spine movement again showed group differences in pattern and range. It would appear that the lumbar spine has compensated for altered frontal plane hip movement but that there is minimal difference in pelvic movement.

10.1.2.1 Hip

The literature reports a wide variety of curve patterns for frontal plane movement in healthy adults but all follow a trend of a movement into adduction until terminal stance and then a movement into abduction through the end of stance phase and into the swing phase, similar to that of the present study. Perron et al (2000) and Kadaba et al (1990) are the only researchers to have published normal frontal plane range at the hip joint along with movement patterns from data collected by research using motion analysis, allowing comparison with data from the present study.

The THN group, in the present study, had mean frontal plane hip range of 11.61±4.46° which is comparable to that of Kadaba et al (1990) who found 11.6° in the 40 healthy people (no age given). Bennett et al (2006) report a mean range of 12.86° in 10 healthy controls (64±3.6yrs) which is larger than that of Kadaba et al and that of the present

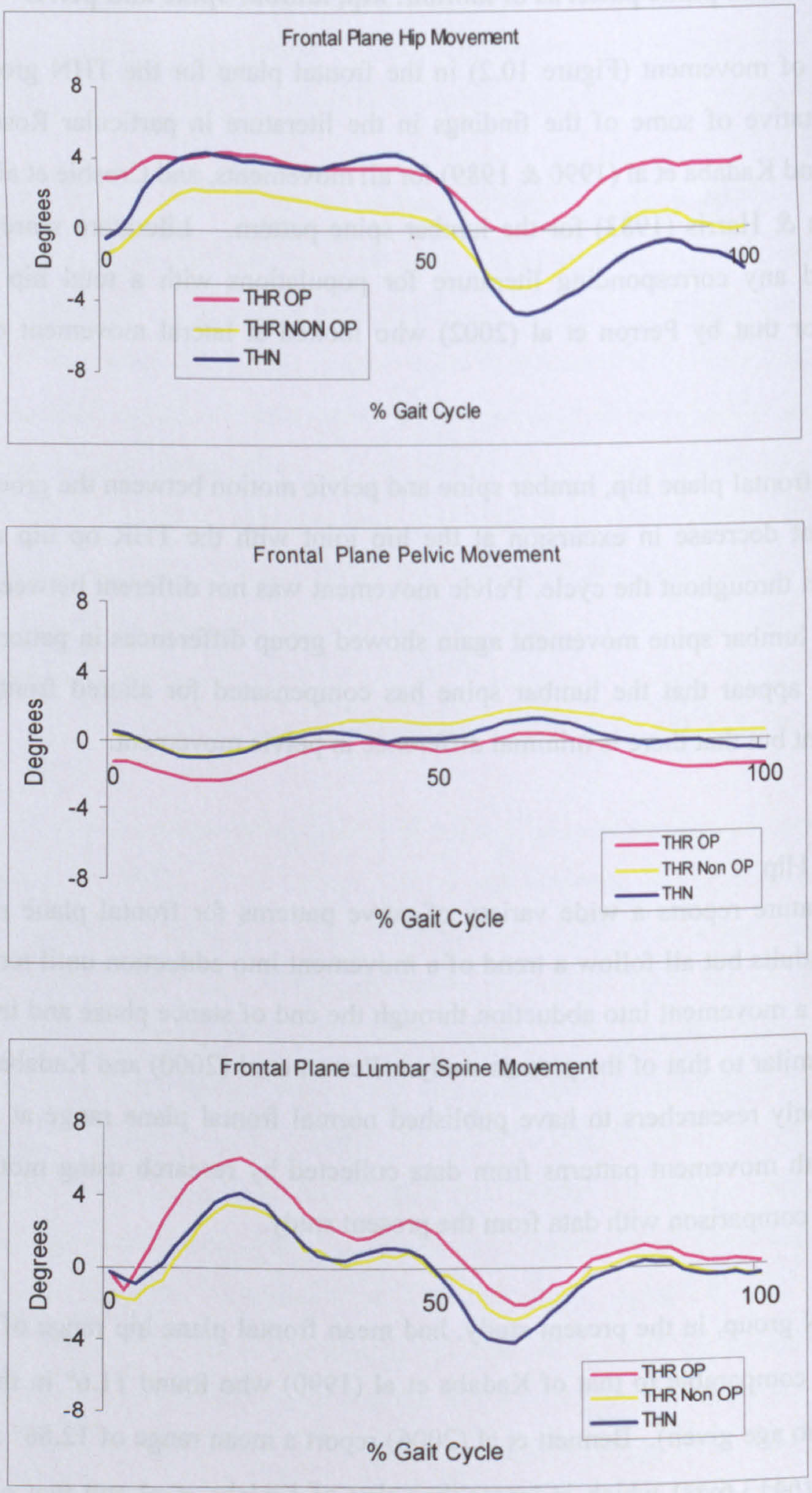


Figure 10.2 Frontal plane movements of the hip, pelvis and lumbar spine

study. However a mean difference of 1° may reflect marker placement errors. In contrast, Perron et al (2000) report a smaller range of frontal plane hip motion range of approximately 5° (taken from graphical representation) which differs from other published studies and the data from the present study.

Movement patterns in the frontal plane in healthy adults in the current study show a similar pattern to those presented by Rose and Gamble (2006), Perron et al (2002) and Kadaba et al (1990) but particularly Perron and Kadaba. The present study showed the classic two peak adduction pattern with the 1st peak occurring in early stance being marginally larger than the 2nd, with the peak magnitudes of the adduction and abduction being very similar to those of Kadaba, whilst Perron et al (2000) showed the 2nd peak to be larger than the first. The frontal plane pattern of Perron has a smaller overall range of adduction than either the Kadaba or the present study, which may be explained by the gait velocities represented in these studies. The pattern from Kadaba follows the present study more closely with the adduction peak difference in the present study being 0.08° (4.26° for the 1st peak and 4.18° for the 2nd) whilst that of Kadaba appears to be approximately 1.3°.

The small differences in the normal data in the present study are either below or comparable with the error margin of the Kinemetrix motion analysis system (1.29°), which would indicate that these differences may be invalid and that frontal plane hip patterns should be regarded as similar to the published literature.

Frontal plane motion in a THR population has not been published at two years post surgery with the nearest equivalent being Perron et al (2002) who present movement range and hip patterns for patients at approximately 12 months after total hip replacement. The pattern of movement is very similar to that of the present study, except that the Perron study reports a smaller mean range (approx. 3°) compared to 4.32° from the present study, again the difference between these two studies corresponds to the error margin of the Kinemetrix system. Bennett et al (2006) assessed 8 patients (age 60.8±5.8°) at 6 weeks post THR finding a mean of 7.6° of motion. This value is higher than that in either the present study or that of Perron et al but this may be due to the short post op time scale, when hip abductor and adductor strength is much weaker and swelling of the thigh and pain may be present, giving a larger range of frontal plane hip movement.

The data from the present study starts in 3° of adduction whilst that of Perron starts at 8°, so whilst the ranges are similar the offset into adduction is smaller in the present study. Data collected at 12 months post surgery may represent reduced hip abductor strength resulting in increased adduction motion, when at 2 years post surgery (the present study), it may be argued that hip abductor strength should be improved and adduction motion reduced, however muscle strength was not measured in the present study. The difference between the THR op and THN groups shows that hip adduction is still greater in the THR op group, so that relative normality has not been reached by two years post op.

Abduction movement is significantly different between both the THR groups and the THN group but predominantly between the THR op and THN groups. The THR op group only go into marginal abduction (0.12°) whilst the THR non op and THN groups have 4.22° and 3.69° respectively. These results are comparable with those of Kadaba et al (1990) who show 4° of true abduction. In contrast Perron et al (2002) report that both their control and patient group do not have any real abduction with the movement staying in adduction throughout the gait cycle, with a relative adduction of 3.5° in the control group and 2° in the patient group.

Loss of abduction in the THR op group in the present study indicates that patients at two years post THR either drop their pelvis to the opposite side and /or have reduced hip abductor strength. In either scenario loss of hip abduction would mean that the lumbar spine or pelvis must move in an altered pattern to allow efficient movement in the frontal plane.

10.1.2.2 Pelvis

Frontal plane motion at the pelvis in the present study showed no significant difference between the three groups with ranges of 4.46±1.56°, 4.63 ±1.63°, and 4.47±1.53° for the THR op, non op and THN group respectively. These mean ranges are smaller than those reported in the literature for age matched healthy equivalents which range from 5±2° (Judge et al 1995) to 7.72±2.26° (Whittle & Levine, 1999), Table 4.7, p89A, gives full ranges from the literature. The ranges from the present study fall within one standard deviation of the published results and could be partly explained by the slower walking speed compared to the values from the literature (Stokes et al, 1989). The low values for pelvic movement particularly in the THN group may be due to the variability of movement in each of the participants. Mean data for range, and at heel strike and toe off, is represented in the present study, this reduces the data to a single value and does not give recognition to the variance. This is especially so for the pattern of pelvic movement where a future project with a larger sample size would be needed to assess if variety in patterns of pelvic movement during gait concurred with the results from this study.

The pattern of motion of the pelvis in the THN group is similar to published literature especially Crosbie et al (1997), Thurston (1985) and Thurston & Harris (1983) except that the peaks of lateral hitch are less pronounced in the present study. Noticeably the THR groups follow the same pattern as that of the THN group but the THR op pattern falls into more pelvic tilt to the non weight-bearing side throughout the gait cycle. Conversely the THR non op group have more tilt to the weight-bearing side particularly through the terminal stance, pre-swing and the swing phases. This would imply that there is less control of the THR op side of the pelvis so that the opposite side drops particularly through weight-bearing, where the biggest magnitude difference during stance is represented (1.34°). The pelvis stays dipped to the opposite side through the swing phase showing that either the hip abductors are weak and cannot elevate the pelvis on the opposite side or that the trunk is leaning to the weight-bearing side and there is a relative drop of the pelvis to the non weight-bearing side. The former suggestion cannot be supported as muscle activity was not recorded however Figure 10.2 clearly shows that whilst the pelvis is dropped to the opposite side the lumbar spine shows a lean to the weigh-bearing side. It would appear that a compensatory pattern has developed where the lumbar spine and pelvis work to counterbalance effort.

At key points in the gait cycle the pelvis has a reciprocal movement pattern to that of the lumbar spine. Although there are no significant differences between the ranges and the peak magnitude differences are small (1.42° stance and 1.62° swing) and may partly be accounted for my systematic measurement error they are present and show that at two years post operation people with THR have altered motion.

10.1.2.3 Lumbar Spine

The pattern of frontal plane motion for the THN group in the present study is similar to that described by Thurston & Harris (1983) and Crosbie et al (1997a) although both of these authors show a higher first lateral flexion peak to the weight-bearing side. Likewise the dip into reduced lateral flexion to the non weight-bearing side at pre-swing is larger than that found in the present study.

Frontal plane patterns of motion for the THR op and non op groups followed that of the THN patern but the magnitude of the THR op was greater for lateral flexion to the weight-bearing side than either of the THR non op or THN groups. There was however a contrast in lateral flexion to the non weight-bearing side where the THR op group had the smallest magnitude. The THR op movement indicates that this group hold themselves in more lateral lean to the weight-bearing side during walking and do not shift the trunk across the midline as successfully as the THN group. Lateral lean to the weight-bearing side may be an attempt to reduce the hip abduction moment thus reducing the effort of weight-bearing (MacKinnon & Winter, 1993). The THR non op side shows less lateral excursion to either side than either the THR op or THN groups and it is suggested that this may be a result of the lean to the THR side on weight-bearing.

A statistically significant difference (p=0.017) was found between frontal plane lumbar spine motion between the groups when tested by ANOVA, the mean range for the THR op (8.17± 2.48°), and THN (8.27± 1.88°), groups are larger than that for the THR non op group (6.56±2.39°). The THR non op group had the smallest range which was significantly different compared to the THR op (p=0.014) and THN (p=0.008) groups.

Both Thurston & Harris (1983) and Crosbie et al (1997a) recorded data in healthy participants of a similar age. Crosbie et al (1997a) measured lateral flexion to be 9±2.5° in their control group of 108 participants (age 20-82 years), whilst Thurston & Harris (1983) (n=48, age range 16 -74 years) reported a slightly smaller mean range of 8.5±2.1°, both these results are comparable to the data of the THN and THR op groups but higher than the THR non op group.

Using a younger population Thurston (1985) reported a mean frontal plane range of 6.8± 1.81° in their control group which is comparable to the THR non op group but less than the THN and THR op results in the present study, whilst Whittle & Levine (1999) reported a mean range of 7.55±1.65° in 20 healthy young men (21-39 years). Sartor et al (2002) recorded a range of 12° with 6° to the weight-bearing side through the stance phase and 6° to the non weight-bearing side through the swing phase in 17 participants (28 range 21-47yrs), no walking velocity was cited by Sartor. The data from the present study was collected on older participants so cannot be directly compared with the data above. It is well recognised, however, that older people adopt gait patterns to assist failing dynamic balance (Winter et al, 1990) by adopting a wider base of support, shorter step length and reduced push off in stance. The author suggests that increased lumbar spine frontal plane motion seen in the present study in the THN and THR op groups may be present to help to maintain a balanced walking pattern, whilst the THR nonop group have reduced range because the spine is held laterally towards the operated side.

No literature reports measuring lumbar spine movement during over ground walking in the frontal plane post total hip replacement using an optoelectronic measurement system. The nearest comparable measures are with trunk tilt (Vogt et al, 2003a) or lateral manubrium displacement and lateral pelvic movement (Perron et al, 2000) where comparisons of direction trends can be undertaken.

Using a patient population after THR, Vogt et al (2003a) reported lateral total trunk tilt to be a mean 2.9° towards the operated side and 2.7° tilt to the non operated side in 12 patients (61.5±6.7 years) at 3.5 – 6 weeks post surgery, with two thirds of patients having an overall mean trunk lean to the operated side whilst walking. The overall range of 5.6° is lower than both the THR op and non op sides measured in the present study. Vogt et al also assessed trunk tilt in 10 controls (59.5±6.1years) and showed their mean range to be 5.2°, which is less than that measured in the THN group in the present study and to that reported in the published literature. The participants in Vogt et al's study were measured using an ultrasonic movement analysis system with markers on the S_1 and the T_9 spinous processes, with the thoracic marker being placed higher than in the present study (T_{12}). Physiological lateral movement of the trunk combines equally from the lumbar region and the whole of the thoracic region (Kapandji, 1990), however the majority of thoracic movement occurs around the T_{3-8} region (White & Panjabi, 1976) and movement of the lower thorax is restricted as the thoracolumbar region is biomechanically stiffer. Placement of the marker on the T_{12} gives lumbar spine movement only whilst a marker at T_9 allows some thoracic motion but this is stiffer than the lumbar region hence the overall range may have limited some of the possible excursion.

The participants in the Vogt et al (2003a) study walked on a treadmill at speeds considerably faster than the present study (2.1m/s and 3.0m/s for the patient and control groups respectively) and it was expected that this would have increased the lateral displacement of the trunk rather than reduced it (Stokes et al, 1989). The healthy control group (30.4±3.4 years) had a mean of 4° of lateral spinal movement. It appears however that the lumbar spine movement data from the Vogt et al study does not relate to similar data by Taylor et al (1999) who assessed lumbar spine and pelvic movement in 14 healthy people (age 20.6±2.8 years) reporting 11.98±1.86° of frontal plane motion when walking on a treadmill at lower self selected walking speed of 1.33±0.28m/s.

It appears that as Stokes et al, 1989 demonstrated walking at increased velocities combines with an increase in pelvic movement and consequentially trunk movement. However the results from the Vogt et al are still considerably smaller than those from the present study despite walking at a faster velocity but this cannot be explained by the use of the treadmill as the results from Taylor et al (1999) show.

Perron et al (2000) measured lateral manubrium displacement and lateral pelvic movement in 18 women, 12 months after THR surgery and compared this with data from 15 healthy controls. The THR group had 50% more lateral manubrium displacement (p=0.0003) but no difference in pelvic displacement. The Perron paper includes full trunk and head movement and these authors did not assess how much movement took place at specific body segments. The present study does not show a 50% increase in lateral lumbar spine movement for the THR groups, so it could be suggested that the increased movement found by Perron was due to head or thoracic motion. This is supported by the findings of Murray et al (1972) and (1979) who reported lateral tilt of the head to the operated side in patients with THR. Further research on whole trunk and cervical spine motion in patients with THR would ascertain where the specific increased motion recorded by Perron originated. As there is no literature measuring lumbar spine movement in the frontal plane, the Perron paper gives the nearest representation of lateral spinal motion in patients with THR.

Frontal plane lumbar spine movement both dynamic tilt and posture asymmetry are important to understanding gait abnormalities. The results from the present study show significant differences between the THR op and THN groups but not with the THR non op. Further research on larger numbers of participants including static measurement of frontal plane alignment in standing and walking may give clearer understanding of the implications of increased lateral excursion.

Although the width of the walkway was not highlighted to the participants the use of a single force plate required them to walk in a narrow pathway, this may have restricted the base of support and hence frontal plane movement. Slower speeds require less frontal plane pelvic movement (Crosbie et al, 1997) as segmental velocity is lower, with a smaller stride length the pelvis does not have to hitch to the same extent.

Overall the THR participants appear to have an adducted hip, a lateral lean of the lumbar spine to the operated weight-bearing side and a dip of the pelvis to the non weight-bearing side in the frontal plane. These postures balance each other as the peak lateral lean of the lumbar spine and the peak dip of the pelvis (3.82°) reach approximately the same magnitude as the relative hip adduction (4.29°) in the THR op group. A balance can also be found in the THR non op group but the peak magnitudes are less especially at the lumbar spine further highlighting the issue that in the frontal plane the THR op side require more lateral lumbar lean. Compensations at the lumbar spine results in a shift in posture to the operated side which shows by the reduced excursion past the mid line from the THR side to the non operated side, this is not the case on the non THR side where the pattern of motion is similar to that of the THN group.

Further exploration is need on the role of frontal plane spinal/ pelvic movement on balance in the healthy elderly and in participants with pathology. Winter (1990) has identified changing gait variables to accommodate for balance alterations in older people but did not look at the spine but in a later paper MacKinnon & Winter (1990) acknowledge that spinal control plays a major part in controlling balance during gait.

10.1.3 Horizontal plane patterns of motion: hip, lumbar spine and pelvis

Horizontal plane movement at the hip, lumbar spine and pelvis show clear differences between the three groups (THR op, non op and THN) (Figure 10.3) both in the pattern of movement and the mean range of motion. The results show large variability in each of the three groups and therefore the mean differences have to be viewed with caution as not all participants show the mean trends.

10.1.3.1 Hip

Horizontal plane patterns for all three groups at the hip show that the hip lies in lateral rotation throughout the gait cycle although there are two periods of decreased rotation, which are more pronounced in the THN group. The pattern has two peaks of increased lateral rotation for all three groups, however these fall at different times in the gait cycle for the THR and THN groups. The patterns differ to those in the published literature, Perron et al (2000) and Kadaba et al (1990) for normal hip movement however the results from these authors also differ to each other, with the results from the literature being inconsistent. Kadaba et al show a slow progression from 5° of lateral rotation at heel strike to 5° of medial rotation at terminal swing, giving a range of 10°. Whilst Perron et al show an alternating pattern with four peaks in lateral rotation and two towards in medial. The present study shows no shift over the neutral line into medial rotation, similar to that of Perron et al (2002) but does not have the same number of changes in the direction of rotation. The variable results may represent the difficulties of collecting and analysing horizontal plane data (Cheng et al, 2000b) or in the placement of the thigh marker (Baker et al, 1999).

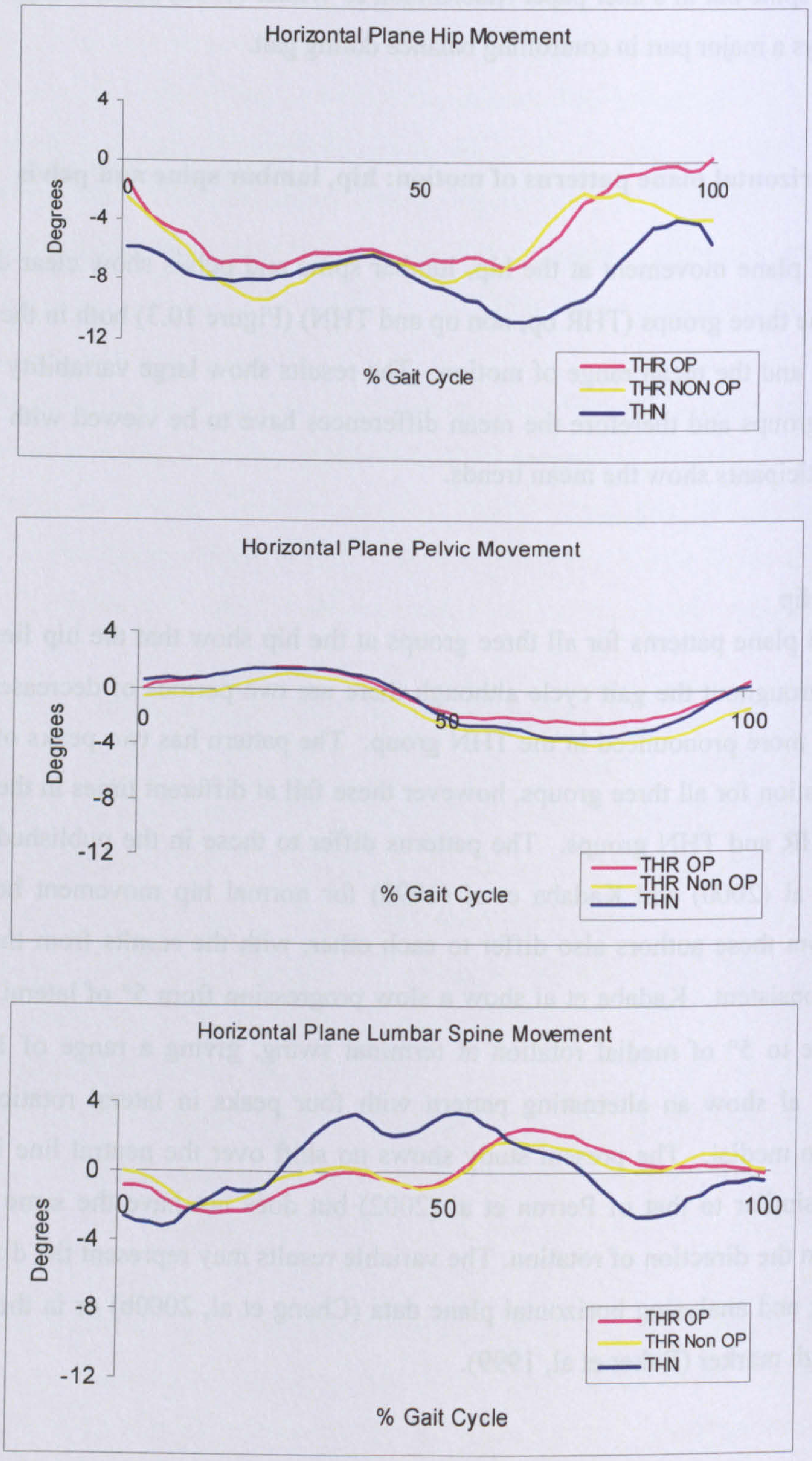


Figure 10.3 Horizontal plane movements of the hip, pelvis and lumbar spine

Mean range of hip horizontal plane hip rotation of 7.44±3.15°, 6.71±3.7°, 9.55±3.81°, was recorded during the present study, for the THR op, THR non op and THN groups respectively and there was no statistical difference between the groups when tested by one way ANOVA. The values from the present study fall mid way between those of Kadaba et al (1990) who report a 10° range of rotation and Perron et al (2002) who cite a range of 6°. The results for the THN group in the present study being closer in magnitude to that of Kadaba et al. for healthy participants. Bennett et al (2006) report a larger mean rotation of 9.46±6.82° in a group of healthy elderly (60.8±5.8 years) when they compared their patients with a hip replacement. No reason for the disparity can be identified from the literature unless specific marker placement issues, not explained in the respective methodology, may give rise to these differences. Thigh or greater trochanter marker positions in particular may give rise to the calculation differences seen in the literature (Baker et al, 1999).

The results of the THR op and non op groups are smaller than those reported by Whatling et al (2006), 11.58±2.98°, in a group of 10 people with a total hip replacement but no age or length of time since surgery have been reported. Similarly, Bennett et al (2006) reported a mean range of 11.5° in their hip replacement group at six weeks post operation (n=8, age 60.8±5.8 years), whilst Stauffer et al (1974) found a mean of 7.4° in 25 patients following THR surgery. It is difficult to compare the finding from the present study to those in the literature as those who have published rotation data in THR patients undertook their research either early post op or no post operative times have been given. The results in the present study (7.44±3.15° THR op, 6.71±3.7° THR non op) are however similar to those of Stauffer et al (1974).

The standard deviations provided in the present study and those in the published literature are large demonstrating the variability in hip joint rotation in both control and hip replacement groups and this may be the cause of the variation in research findings. Hip rotation is a complex movement to measure particularly as marker error can significantly influence the degree of movement (Baker et al, 1999). Delp and Maloney (1993) reported that a 2cm shift in placement of a marker can cause significant change in results so if each of these authors used a calculated hip joint centre which was 2cm different to the other a significant change in hip rotation would occur. The marker system used may also have an effect on the movement outcome; Whatling et al (2006) used a modified Helen Hayes marker configuration, where the present study used the Bell marker system for calculation of hip joint centre. Perron et al (2002) do not identify a particular marker system. Calculated differences in horizontal plane measures may arise because of the use of different marker systems or that different marker placements may give rise to errors in the calculation. The error in hip marker placement for this study was less than 0.2°±0.16° in any plane, whilst at the lumbar spine and pelvis the marker error was 1.7°±0.98°.

10.1.3.2 Pelvis

Horizontal plane pelvic motion in healthy adults shows a two peak pattern of rotation with one forward rotation on the weight-bearing side and one backward rotation which is in agreement with Thurston (1985) and Thurston & Harris (1983). In contrast Crosbie et al (1997) show a triple rotation to both the weight-bearing and the non weight-bearing sides with small angles of less than 2°. The first rotation was forward on the weight-bearing side in early stance and then the pelvis rotated backwards on this side at approximately 20% of the gait cycle. Forward rotations then occurred at 30% and 70% and backward rotations at 50% and 80%.

The THN pelvic pattern of the present study is similar to that found by Kadaba et al (1989, 1990), Thurston (1985) and Thurston & Harris (1983) who identify forward rotation to the weight-bearing side through early stance phase followed by a backward rotation from the end of terminal stance through pre-swing to the end of the swing phases. The THR non op data shows a decrease in forward rotation and an increased backward rotation compared to the THR op and THN groups, whilst the THR op data showed a decreased excursion of backward rotation from terminal stance through the swing phase.

Backward rotation of the THR op side would correspond to simultaneous forward rotation of the THR non op side and vice versa. It is surprising that backward rotation of the operated side has a smaller excursion given the loss of sagittal plane hip extension, as it is well recognised that reduced hip extension is compensated for by increased backward rotation of the pelvis (Norkin & Levangie, 1992; Perry, 1992). Reduced hip extension can also be compensated by increased sagittal plane lumbar movement and increased posterior tilt angle of the pelvis (Murray et al 1971), both of which occur in the present study. Increased backward rotation on the THR non op side would allow an increased step length on the operated side and more efficient push off onto the operated limb at the start of stance phase. Step length has not been calculated for the present study but this could be explored in future research. Differences in walking velocity also change pelvic rotation (Stokes et al, 1989) with increased walking velocity requiring a larger degree of motion.

Thurston & Harris (1983) and Thurston (1985) show a notch on the pelvic backward rotation curve and this is evident for the THN group only occurring at approximately 60% of the GC, similar to that of the authors mentioned above. The notch is also found in lumbar spine motion but occurs earlier in the cycle.

The mean range of rotation at the pelvis was 10.1±3.4° from Thurston & Harris (1983), 10.1±4.17° Thurston (1985) and 9.2° (no SD given), Kadaba et al (1990) whilst Crosbie et al (1997) had a mean range of 4±2.5°. The Thurston and Kadaba results are larger than the mean range of pelvic rotation from the present study (8.11±°2.27 for the THN, 7.46±1.77°, for the THR op and 8.26±2.51° for the THR non op groups), whilst those from Crosbie et al are considerably smaller. Unfortunately no walking velocity data was recorded in the Thurston papers but the participants in this study walked at a similar speed to that of Crosbie et al so relative velocity cannot account for the differences. The mean range differences between the THR groups and the THN group in the present study were not significant when tested by one way ANOVA and the standard deviations for all groups were large showing variation in individual and group performance (Appendix X).

10.1.3.3 Lumbar Spine

Lumbar spine motion predominates in the sagittal and frontal planes with some concomitant motion in the horizontal plane but this is limited due to the shape of the facet joints in the lumbar region. Some horizontal plane rotation may be explained by skin movement over the T_{12} marker in particular but reliability results from the present study (Table 5.2) show that horizontal rotation in particular has a low least significant difference, so skin movement errors do not impede repeatability in this study. The debate between the use of skin markers versus plates may explain some of the differences in the literature and therefore the data will be different depending on the fixation device used.

Several authors have measured lumbar spine motion in the horizontal plane in healthy adults giving mean ranges of 4.5±2° (Crosbie et al, 1997), 8.8±2.49° (Thurston, 1985) and 8.3±2° (Thurston & Harris, 1983). The results from all three groups from the present study fall in the middle of these published values (THR op 4.88±2.41°, THR non op 3.78±1.76°, and THN 6.82±2.2°), with the THN values being significantly greater when tested by one way ANOVA. Post hoc t-tests showed significant differences between the THR groups and the THN data ($p=0.006$ op and $p<0.00001$ non op) and interestingly the patterns of movement for all three groups were very different.

The pattern for the THN group follows the expected pattern outlined but Crosbie et al (1997), Thurston (1985) and Thurston & Harris (1983) with the excursions being less in the Crosbie et al study as discussed above. The pattern for the THR groups however was very different and has similar qualities to the pattern reported by Thurston (1985) for patients with OA of the hip. There is diminished rotation throughout the stance phase of gait in both the THR op and non op groups and it is only in pre-swing and initial swing (64 & 62% of GC) that lumbar spine forward rotation occurs (2.53° op and 1.73° non op), these values are smaller and occur later than the forward rotation of the THN group (36 & 52% of GC, 3.43° & 3.48° respectively).

The main difference between the movement patterns is the timing of the peaks of rotation. The THN group pattern has two periods of backward lumbar spine rotation; the first at loading response 6% (-3.21°) and the second at mid swing 80-82% of GC (-2.64°). The THR groups only had one period of backward rotation at 14% of GC (-1.92° non op and -2.35° op sides). Lumbar spine rotation in the THR groups starts in backward rotation when the limb is in the mid stance sub phase and changes to forward rotation during pre-swing into initial swing. Backward rotation at midstance may help to stabilise the trunk on the hip and help with progression of weight- bearing, whilst forward rotation in pre-swing/ initial swing may help to give momentum to progress the swinging limb. At a concurrent point of the gait cycle, in both the THR groups, the pelvis rotates backwards to approximately the same extent as forward rotation of the lumbar spine, whilst simultaneously the hip is in the second peak of lateral rotation. Although small excursions take place there is a balanced compensation between the hip, lumbar spine and pelvis, to keep the trunk head in a forward motion.

The pattern of the THN group demonstrates a reciprocal compensation between the pelvis, lumbar spine and hip so that as the hip rotates into more lateral rotation, the pelvis is in forward rotation and the lumbar spine in backward rotation whilst the opposite occurs when the hip moves into less lateral rotation (42% of GC Terminal stance). The pelvis moves through neutral from forward to backward rotation and the lumbar spine is in forward rotation but with a notch of a slight dip towards neutral. The period of terminal stance is a double support phase where transition is starting with weight transference from one foot to the other, maximal rotation at this point allows efficiency of movement. Thurston & Harris (1983) and Thurston (1985) both show a notch on the forward rotation of the lumbar spine with a corresponding similar notch in pelvic backward rotation occurring after lumbar spine motion. These authors report that the notch coincides with the toe off on the opposite limb at approximately 53% of the GC. A similar notch was found in the present study occurring at a mean of 46% of the GC but individual variation was present. The notch signifies the mid point in horizontal plane pattern of the lumbar spine and is not seen in either of the THR groups.

Subject variation in the horizontal plane in the present study is high as reported by previous researchers (Crosbie and Vachalathi, 1997; Murray et al, 1964) and this has influenced the overall mean patterns and timing of movement. Although horizontal plane motion and lumbar spine motion in particular were not analysed for specific movement pattern identification, in the present study, this may be useful to look for trends of post operative adaptation. Crosbie and Vachalathi (1997) suggest that pelvic rotation in the horizontal plane in healthy young adults may not be a useful measure of gait due to high inter-subject variation and that pelvic motion changes within the individual depending on attitude. As the THR group had a very different pattern of motion to that of the THN group it could be argued that further research is needed to identify individual horizontal plane motion patterns in the patients post hip replacement, where repeated movement patterns during gait could be collated to review individual variance and therefore help to define movement efficiency.

10.2 MOTION AT HEEL STRIKE AND TOE OFF

Measurement of hip, pelvis and lumbar spine angle at the point of the gait cycle at heel strike (initial contact) and toe off (pre swing) was undertaken to assess any variance between the groups at the start and the end of the stance phase. Heel strike was defined as the point the foot contacted the force plate registering a vertical value whilst toe off was defined as the point immediately after no force plate readings were registering. Toe off occurred at an average of 63.9%, 63.36% and 61.09% of the gait cycle for the THR op, THR non op and THN groups respectively.

Hip motion in the sagittal and frontal plane at heel strike and toe off showed significant differences between all three groups. There were no significant differences in horizontal plane position between the three groups for either hip or lumbar spine motion and for the sagittal and frontal plane in the lumbar spine mainly due to the large degree of variance represented by the large standard deviations.

10.2.1 Heel strike

At heel strike the THR op group had the least sagittal and horizontal plane hip movement and the largest motion in the frontal plane. Whilst at the lumbar spine the THR op group had more sagittal and frontal plane motion and less horizontal plane motion compared to the THN group. The differences at heel strike for either the hip or lumbar spine were small but significant and were representative of the comparative overall reduction in sagittal and frontal plane motion in the THR op group through the gait cycle.

The average position of the hip in the sagittal plane at heel strike was 29.95°, 29.05° and 25.45° in the THN, THR non op and THR op groups respectively. Few researchers have reported hip or lumbar spine position at specific gait events but data can be extracted from angle time graphs presented by some of the authors. The results from the present study compare with those of others for healthy individuals for both the sagittal and frontal planes at heel strike. As discussed in section 10.1.1.1 researchers report a variety of hip movement or position depending on the instrumentation used and this may explain why the literature reports a variance at heel strike from 31° Murray et al (1964), 20° (Rowe et al, 1989), 35° Kadaba et al (1990), 23±8° Kuster et al (1995), 25° Crosbie & Vachalathiti (1997), or 24° Perron et al (2000).

Lumbar spine position at heel strike for the three groups of the present study did not show any significant differences for any plane of motion due to the high degree of variance. The lumbar spine was held in a neutral position at heel strike with no more than a ±4° variation in any plane, with frontal plane having the largest offset to the non weight bearing side of between 2.80° to 3.75° for the THR non op and THN groups. Variance in the position of the lumbar spine was less than 2°in the sagittal and 2° in the horizontal planes. These values agree with those in the literature for healthy participants which show a large range particularly in the frontal plane where Whittle & Levine (1999) report a lumbar spine position of 4° at heel strike and a pelvic position of 22°. The other researchers report more moderate results of between -4° (Thurston & Harris, 1983), -2° (Thurston, 1985), 0° Crosbie et al, 1997a). There is no published lumbar spine research using a marker plate system and this may explain the differences.

Vogt et al (2003) compared pelvic movement using a plate and direct skin markers finding that the plate consistently demonstrated less coefficient of variation on repeated trials. The data from the present study emulates the plate data of Vogt et al (2003) for the pelvis in both the frontal and horizontal planes with a maximum of ±2° in either plane. In the sagittal plane the present study shows the pelvis to be held in 3.73° for the THN group whilst Vogt et al report a position of approximately 1° (taken from graph) for plate marker system and -0.5° for skin markers.

Whittle & Levine report larger readings for sagittal plane pelvic position (11°) however in contrast Thurston (1985) and Thurston & Harris (1983) report smaller positions of -1°

and 0.5° respectively. The results from Vogt et al, Thurston and Thurston & Harris are on younger populations than the present study and this may partly explain the difference in sagittal plane results added to the difference in marker attachment and position and that all except the results from Thurston and Thurston and Harris were estimates from graphical representation. Interestingly the results from Crosbie et al (1997b) show the nearest comparison to the present study with a pelvis position of -3° in the sagittal plane. Although the results from the present study and the published literature show a degree of difference the systematic error of 1.29° from the present study should be remembered and therefore the results overall and very similar.

10.2.2 Toe Off

At toe off (pre swing) the largest statistically significant difference (p<0.001) between the three groups (THR op, THR non op and THN) occurred at the hip joint in the sagittal plane. The THN group had a mean extended position of -0.64° whilst both the THR op and non op groups held flexion positions of 9.56° and 3.89° respectively. At toe off, the hip moves from the fully extended position at terminal stance through to neutral at mid stance (Perry, 1992) in the gait cycle of healthy participants, however the results from the present study indicate that the THR op group, in particular, were held in flexion which would have a consequential effect on the position of the pelvis and the lumbar spine.

Sagittal plane pelvic (5.62°) and lumbar spine position (3.66°) in the present study are larger than those presented in the literature for healthy participants whilst the position for the THN group (2.27° lumbar spine, 3.29° pelvis) corresponds well with the literature (Thurston & Harris, 1983; Thurston, 1985; Crosbie & Vachalathiti 1997, Crosbie et al, 1997a,b; Vogt et al, 2003). The literature also presents a variation between forward and backward tilt at toe off but with an equal distribution of values and again as the variance is approximately equal to the system error, the values become comparable.

The lack of significant differences between the three groups in the present study is due to the high degree of variance as the standard deviations are large for all measures at all joints. As discussed earlier individual variation in all planes is high for lumbar spine and pelvic motion (Murray et al, 1964; Whittle & Levine, 1995; Crosbie and Vachalathi, 1997; Crosbie et al, 1997b).

This is true in the present study and the mean larger range of lumbar spine motion demonstrated by the THR group in comparison to the THN group (Figure 8.36) indicates that those with a hip replacement have the capacity to be more variable and therefore at any point in the gait cycle the results will differ from the norm. This may be due to poor motor control of the lumbar spine and pelvis or to poor repeatability of the gait pattern. Motor control was not measured in this study and repeatability has not been explored in detail. However as a result of this variability an observational comparison of the variance of the through gait angles was presented in Appendix X. The variability within the groups is clear for all planes and study groups but the greatest variability occurs in the horizontal plane and in all planes of the pelvis and lumbar spine.

The author suggests that it is important to ascertain the range of "normal" motion and position in the pelvic and lumbar spine in a large group of both younger and older participants so that true comparisons can be made to those with pathology or gait abnormalities affecting the lumbar spine- pelvic interaction.

10.3 INTERACTION OF MOVEMENT: ANGLE – ANGLE DIAGRAMS

Angle –angle diagrams allowed the researcher to investigate the relationship between the angle, timing and pattern of movement of two segments in one person or between groups with overlaying patterns getting a comparison between individuals or groups. In this thesis the pattern of interaction for each of the hip/ lumbar spine, hip/ pelvis and lumbar spine/ pelvis for each of the three groups (THR op, THR non op, THN) in each plane were presented. Although angle – time graphs give a comparison of the angles/ patterns of movement in a single plane, ideally clinicians would like to explore 3-dimensional patterns of interaction between hip/ pelvis/ lumbar spine movement. This thesis does not explore how these complex 3-dimensional interactions can be presented but does explore the interactions between the segments by angle-angle diagrams.

Each of the three groups show differences in patterns for all movements in all planes, but there appears to be greater differences in the interactions of hip/ lumbar spine and lumbar spine/ pelvis than the hip/pelvis. There is limited published data on angle-angle diagrams for these interactions, in healthy participants and none in those with hip replacement so unfortunately comparisons cannot be made. The exception is between the lumbar spine and pelvis interactions in the frontal and horizontal planes. These interactions will be discussed followed by a summary of the other planes and interactions.

Whittle & Levine (1999) represented angle-angle diagrams for frontal and horizontal plane movement between the lumbar spine and the pelvis in healthy male participants (n=20, young males). The lumbar spine range of motion from Whittle & Levine (1999) is similar to that found in the present study, but the current study has a smaller degree of pelvic motion in the frontal plane. As Whittle & Levine (1999) used younger participants all of whom were male, gender and age variations may have caused the pattern differences seen in the data.

10.3.1 Frontal Plane lumbar spine and pelvis

Frontal plane interactions show that the pattern flows in the same direction for both the present study and that of Whittle & Levine (1999). They differ however by the steepness of the slopes, as those in the present study are less pronounced because of the smaller degree of pelvic motion and subsequent faster rate of change in movement direction. Full description of the angle-angle diagrams can be found in Chapter 8.5, p186.

Overall the pelvis and lumbar spine in the frontal plane for the THN group move simultaneously except at times of change in support (toe off/ pre swing and terminal swing/ heel strike) when the pelvis remains in a set position whilst the lumbar spine moves a small degree in a stabilising motion, before progressing on. These periods of lumbar spine stabilising are not as pronounced in the Whittle and Levine study and this may be because they studied a younger population, where stability is less of an issue.

The THR op and non op patterns follow the same sequence at the THN group but show more pelvic movement than the THN group and have less pronounced stabilising at the pre swing and terminal swing phases, although this is present. It appears that the THR participants have clear concurrent but opposing movement of the pelvis and lumbar spine throughout the gait cycle with two main points of stabilisation at terminal stance and terminal swing. These are less pronounced than the THN group but are very distinctive for both the THR op and non op data. This may suggest a pattern representing more stability of the lumbar spine on the pelvis in the THR group, where the two segments work together to compensate for lost movement. The THN group have more independent movement between the pelvis and lumbar spine but this is less evident in the THR data despite these participants having more pelvic movement. As the THR group have a loss of hip abduction then this may be a compensatory movement to allow weight transference and loading of the weight-bearing side. At initial limb loading and through the swing phase the lumbar spine is flexed to the non weight-bearing side, whilst from mid stance through to heel off the spine is flexed to the weight-bearing side. This would allow easier weight transference through the weight-bearing (operated) limb so assisting limb loading. When the THR non op side is assessed the pattern is less pronounced but follows the same shape as the THR op data.

Timing of lumbar spine and pelvic motion appears to occur in a similar way within all the three data sets for the present study with a greater velocity through loading response and pre swing phases denoted by the large number of data points over time. This concurs with the data from Whittle and Levine (1999).

10.3.2 Horizontal Plane lumbar spine and pelvis

Horizontal plane pelvic and lumbar spine interactions show a non- synchronized pattern between the two segments. Starting in rotation of the lumbar spine and pelvis to the weight-bearing side at heel strike through loading response the pelvis stays approximately in this position whilst the lumbar spine rotates to the opposite side through stance. At mid stance the lumbar spine is in neutral and the pelvis is in slight rotation to the opposite side and this remains stable until the start of terminal stance when the lumbar spine starts to rotate to the opposite side and this is followed by the pelvis at 50% of the gait cycle the start of pre swing. Through pre swing the pelvis rotates back to neutral with the lumbar spine remaining in rotation to the opposite side. Just after the start of initial swing the pelvis starts to rotate to the weight-bearing side followed by the lumbar spine through mid swing. At this point the pelvis stays in slight forward rotation to the weight-bearing side and the lumbar spine follows. At two points in the gait cycle (heel strike/ loading response and terminal stance/ pre-swing) the pelvis and lumbar spine move in the same rotation but at all other times they move in opposing rotations.

This follows the pattern displayed by Whittle and Levine (1999) but with a smaller degree of lumbar spine rotation in the THN group of the present study the shape outlined by the pattern is different. The younger male subjects of Whittle and Levine show more lumbar spine rotation and an even balance around neutral. The older participants in the

THN group of the present study have a tendency to rotate to the opposite (non weight-bearing) side but have an even rotation around neutral for the pelvis.

The pattern for the THR data is very different to that of the THN group with the lumbar spine starting in slight rotation to the opposite side at heel strike and the pelvis in neutral. The lumbar spine increases the degree of rotation to the opposite side whilst the pelvis rotates to the same side. Through mid stance the pelvis rotates to the same side whilst the lumbar spine stays in approximately the same degree of rotation (-2°) and then at the end of mid stance and into terminal stance the pelvis rotates backwards whilst the lumbar spine stays in neutral until the mid way through terminal stance when it rotates backwards slightly. At the start of pre swing the lumbar spine rotates towards the same side whilst the pelvis maintains position in backward rotation. From this position at initial swing the lumbar spine rotates back to neutral whilst the pelvis slowly increases rotation to the same side. Through mid swing the lumbar spine moves to neutral and stays in this position through to the end of terminal swing whilst the pelvis rotates to neutral and then into forward rotation.

Overall this pattern indicates that the pelvis and lumbar spine at most times are in an opposing coupling motion with the pelvis in more rotation to the opposite side than the lumbar spine which is much more controlled around neutral. The pelvis may compensate for lack of extension at the hip. Lee et al (1997) and Shimada et al (1996) concur that a retracted pelvis (rotation to the non weight-bearing side) occurs excessively when hip extension is limited, as is the case with the THR participants. As lumbar spine motion shows a good range, with an even pattern and constant timing and this would indicate that the spine is able to compensate for the altered pelvic motion.

Other angle-angle interactions

There are no published findings for any of the other angle-angle interactions to directly compare the findings from the present study, however the main differences can be highlighted.

Sagittal and horizontal plane patterns between the lumbar spine/ pelvis, hip/ pelvis and hip/ lumbar spine interactions are not dissimilar between the groups, although the ranges differ especially between the THR op and THN groups.

There are differences in the frontal plane between the hip/ lumbar spine and hip/ pelvis interactions, where not only is the range of motion different but the pattern changes too. The THR op pattern for hip/lumbar spine interaction shows that the hip does not go into abduction but that lateral lumbar side flexion moves towards neutral or the non weight-bearing side to compensate for this from 54-64% of the gait cycle. There is no true lateral lumbar flexion to the non weight bearing side but a shift towards neutral from a lateral position to the weight-bearing side which is moderately fast. The lumbar spine then moves into side flexion to the weight bearing (operated) side from 64 – 82% of the gait cycle whilst the hip into more adduction. The lumbar spine compensates for the loss of hip abduction in order to maintain a balanced posture.

A similar frontal plane interaction can be observed between the hip and pelvis with increased hip adduction the pelvis stays in neutral or a tilt to the non weight-bearing side in the THR op group reinforcing the compensatory pattern displayed by the hip/ lumbar spine interaction. It appears that in the frontal plane, increased hip adduction incurs a compensatory pattern from the pelvis and lumbar spine of concurrent pelvic tilt to the non weight-bearing side and lumbar lateral flexion to the weight-bearing side. It is suggested that the centre of gravity would have to remain over the weight-bearing (operated) foot to reduce the effort and loading to this side.

Hip abduction with lateral spinal flexion does occur when the THR non op pattern is analysed although this does not reach the same degree as that of the THN group.

Lateral lean of the lumbar spine to the weight-bearing side or a neutral position with pelvic tilt to the non weight-bearing side is the compensatory pattern seen in patients with OA hip awaiting THR as described by Watelain et al (2001) and Thurston (1985).

It is unclear why the THR participants in this study had a greater degree of lumbar spine movement and less pelvic movement but this may be due to a habitual pattern to allow faster efficient gait pattern in the absence of full range of hip movement or poor muscle control mainly from weak hip abductors. Murray et al (1975) reported significant reduction hip abductor and adductor strength at 2 years post THR in a group of 83 people aged 63±10 years when compared to healthy normals. Likewise Bhave et al (2005) found that 54% of patients assessed after hip replacement had weak hip abductors, 22% had a tight Tensor Facsia Lata and 14% had a leg length discrepancy. This combination of issues could explain the problems with the population in the present study. The degree of passive physiological hip abduction was significantly less on operated side of the THR group in comparison to the non operated hip (Figure 7.9, Appendix O).

The data presented is the average data for the 24 participants and this does allow recognition of the variance of the data from individual participants. Participant variability is high at times and this is lost on averaging but can be seen in the standard deviations presented in the mean data for range, heel strike and toe off and in the variance graphs in Appendix X. Further research needs to be undertaken to explain the patterns fully and to describe the variance in more detail.

10.4 HIP JOINT MOMENTS

Hip joint moments normalised by body mass were measured in (Nm/kg) for comparison with the published data. Peak hip moments (sagittal = extension, frontal = abduction, horizontal = medial rotation) were significantly different for all three planes, between the THR groups and the THN group, but not between the THR op and non op groups. The differences between the THR op and THN groups were significant in all three planes but only sagittal plane THR non op/ THN differences were significant.

In the present study sagittal plane mean peak moments for the THN group reached peaks of -0.54 Nm/kg, 0.26 Nm/kg in the frontal plane and 0.023 Nm/kg in the horizontal, whilst the THR op group gave a mean peak moment of -0.44Nm/kg in the sagittal plane, 0.3Nm/kg in the frontal and 0.014Nm/kg in the horizontal. The patterns of moments through the gait cycle for each of the three planes are similar to those reported by Schache & Baker (2007) with the exception of the second peak of the horizontal plane, where there is a medial hip rotation moment in the Schache & Baker study but a lateral hip rotation moment in the present study. In the present study there is a lack of internal rotation and thus a resultant loss of possible internal rotation moment. Muscle strength differences may also alter force production (Bergmann et al, 1993). The values of the present study are lower than those of Schache & Baker (2007) (peak hip extension: -0.85 Nm/kg, abduction 0.7 Nm/kg and rotation 0.1 Nm/kg for internal rotation and 0.08 for external) but this may representative of the different ages of the participants (9 healthy adults mean age 19.8±2.1 years).

Difference in hip force requirements have been reported by Stansfield & Nicol (1998) who assessed resultant force normalised to body weight in 40 to 60 years olds (mean age 53 years) finding that a 30% increase in joint force was required for walking in a younger age group when they compared their data to others. The mean age group in the present study was 74.81±4.89 years for the THR group and 73.04±4.05 years for the THN group thus lower peak moments should be expected overall.

Variation in reported hip moments can been seen in the literature with Winter (1987) reporting peak mean hip moments in healthy adults for natural cadence (105.3 steps/min), which are smaller than the current study for the THN group, extension -0.4±0.413 Nm/kg, flexion 0.6±0.317Nm/kg showing a large degree of variation. In contrast Kirkwood et al (1999) report maximum hip joint moments during walking of -0.89 Nm/kg in the sagittal plane and -0.17Nm/kg in the frontal plane in 30 healthy older participants of 55 years and over. Walking velocity was not reported by Kirkwood et al and this may reflect the differences in hip moments from the results of Winter (1987) and those in the present study.

Variation in the standard deviations of calculated peak hip moments of between 10-30% has been reported Winter (1987), whilst Brand et al (1994) indicated similar variance in measured hip moments at three months post total hip replacement. Differences between study populations can be expected due to large standard deviations which are suggested to be due to cycle–to–cycle variations (Brand et al, 1994). These researchers propose that if cycle-to-cycle comparison could be made within and between studies this variance would decrease.

The THR op group generated significantly smaller peak hip extension moments than the THN group (p=0.0004), indicating that the THR group either did not require the same degree of extension moment or could not generate it. Although walking velocity was not significantly different between the three groups Crowinshield et al (1978a) indicate that hip forces increase by approximately 0.2x body weight for each 0.1m/s increase walking velocity explaining possibly some of the difference in generated hip moments. It could be suggested that as a result of the difference in hip motion and velocity, the degree of sagittal plane hip moment required would be dissimilar between the groups in agreement with the research by Brand et al (1994). The THR participants were not able to generate the same degree of extensor moment as the THR non op or THN groups.

The range of hip extension was found to be significantly limited in the THR participants and therefore the capacity to generate hip extension moment through the range needed to achieve adequate walking velocity and power was limited. After THR the literature reports that hip muscle strength in particular the extensor and abductors muscle groups, are weaker than that of a healthy population (Sashika et al, 1996; Shih et al, 1994; Minns et al, 1993; Cahalan et al, 1989; Murray et al, 1975; Olsen et al, 1972). Differences also occur between the operated and non operated sides for up to one year post surgery (Trudelle-Jackson et al, 2002) but no research has been undertaken to ascertain if strength improves after this time.

Peak frontal plane moments were significantly larger (p=0.015) in the THR op group to the THN group, with no difference between the THR op and non op sides nor the THR non op to THN. The mean range of frontal plane moments was not significant between any of the groups. Larger hip abduction loads imply that the THR op side participants are loading the side more or have to generate a greater moment to get the movement pattern.

Maximal mean frontal plane moments in patients post total hip replacement were reported by Whatling et al (2006) to be 0.9±0.2 Nm/kg. These values are considerably larger than those in the present study but may be indicative of different gait speed or reduced hip abductor muscle activity indicating weaker hip abductor strength and reduced abductor moment. No length of time since surgery or walking velocity was mentioned in the Whatling et al study so this comparison cannot be made. Winter (1987) showed that change to walking velocity alters the magnitude and timing of the peak moments, particularly when people walk at a faster cadence (123.1 steps/min) when the extension peak moment occurs earlier and increases in magnitude, the reverse occurs when walking slowly (86.8 steps/min). Stansfield et al (2001) reported mean peak joint moments which follow similar magnitude changes with alterations in walking speed, but these results were in children and not on the mature adult gait.

As mentioned previously, Crowinshield et al (1978a) compared gait in younger and older healthy participants showing that peak moments are dependent on walking speed with the flexion/extension moment particularly increasing with velocity change. This would justify the difference in hip moments between the groups of the present study. The THR group walked at a slower speed than the THN group and this could have accounted for the smaller sagittal plane peak hip moments. Kotzar et al (1991) found smaller force values to those of Crowinshield et al but the change in values with change in velocity were higher in the Kotzar study. These disparities may be as a result of the comparison between patients from 23 – 58 days post operative recovery (Kotzar et al, 1991) to a healthy young and older age population (Crowinshield et al, 1978a).

Increased cadence can be used to maintain walking velocity and in doing so frontal plane moment demands, angular velocity, are increased at either the hip or the knee to maintain stability during walking (Watelain et al, 2000). This may represent a compensation mechanism adopted after total hip replacement, to try to provide a functional walking speed because of reduced hip extension and flexion. In the present study the time spent in the stance phase was significantly greater in the THR op group compared to the THN group (63.91%, 61.09% respectively) agreeing with the results of Loizeau et al (1995). This may further add to the reasons for the resulting increased frontal plane torque demand.

Reduced hip abductor activity in single stance associated with poor trunk control has been hypothesised by Loizeau et al (1995) in patients after hip replacement (mean 3.8 years). Poor trunk control was a possible issue in the present study as lateral lumbar spine motion was reduced in the THR group (Figure 8.36) compared to the THR non op side with trunk lean to the operated side through the majority of the gait cycle (Figure 3.4). The author suggests that after total hip replacement frontal plane compensatory strategies need to be adopted to maintain a practical walking pattern which demands an increase in the frontal plane hip moment (Figure 8.56).

Horizontal plane moments are not often reported as they are so small and it is felt that comparison is difficult for this variable. The only paper reporting these is by Kadaba et al (1989) who used % Nm/(BWxLL) as units of measurement to report the moments in healthy participants, so the results cannot be directly compared except for the pattern of the moments through the gait cycle. The pattern from the present study compares favourably with that of Kadaba et al except that in the present study there is a larger second peak of lateral rotation moment at approximately 46-48% of the gait cycle. The second peak occurs in the Kadaba et al study but is smaller and later, 60% of the gait cycle. In the present study the participants all walked at a slightly slower pace to that in other studies reporting hip moments and this may have contributed to this changed pattern.

Kadaba et al (1989) also reported sagittal and frontal plane moments in healthy adults giving peak moments of +15% and +5% Nm(BW*Leg length) in the sagittal plane. The pattern of moments over the gait cycle is very similar to that found in the present study taking into account that Kadaba et al report external moments, so the pattern is in reverse to that in the present study. Likewise the pattern and values of hip moments from Stansfield et al (2001) are similar to the present study.

Although moment-angle graphs have not been presented by many other authors the comparison and interpretation of the patterns from differing groups with hip/ gait pathology may help to give a clearer understanding of the movement abnormalities and help clinicians to assess gait more efficiently. The sagittal plane moment –angle graph presented in this thesis is an attempt to do that. Kuster et al (1995) report that the initial flexor moment occurs during the first 5% of the gait cycle in the healthy gait cycle before the extensor moment starts and the findings for all three groups from this study would concur with that. All the groups change to an extensor moment at approximately 5% of the gait cycle and remain in this pattern until 74% THN, 76% THR op and 78% THR non op of the gait cycle, again the later change back to a flexion moment concur with the timings outlined by Kuster et al (1995).

Frigo et al (1996) report a normalised moment-angle for sagittal plane motion in nine healthy adults (mean age 28±5 years), as the units of torque are different to those in the present study the values cannot be compared but the pattern displayed is similar to that in the present study. The main difference lies in the first moment loop which runs anticlockwise in the Frigo study and lasts for a longer period of time: up to 20% of the gait cycle. As the participants of the Frigo study are considerably younger than those in the present study this may explain the delay in moving from a flexion to an extension moment. Hip flexion in younger adults is greater during gait than for older people (Judge et al, 1995) and in older people is accompanied by a reduction in both step length and ankle plantar flexion to accommodate for modifying balance reactions (Winter et al, 1990). Hence the flexor moment demand will be less and this quickly changes to an extensor demand with the reduction in hip flexion and ankle plantar flexion, as weight is accepted onto the foot and then the leg moves over the foot.

The extensor moment presented in the Frigo study is smoother than that in the present study and again may be explained by age but more importantly there is only a small moment magnitude change as the hip moves from mid stance into terminal stance and pre swing. The results from the present study show a greater magnitude difference between the moments at mid stance and toe off.

As this type of presentation has not been used before direct comparisons are not possible, however, it is the pattern of interaction that is important and this research identifies significant differences between the three groups: THR op, THR non op, THN.

10.5 IMPLICATIONS

This study shows that significantly altered movement patterns are present in all three planes of motion at the hip and lumbar spine in participants at two years after total hip replacement. The combination of loss of movement at the hip joint with increased lumbar spine motion during gait significantly changes the mechanics for walking and must have ongoing clinical implications for individuals, and for the management provision of patients with THR in the future.

Individuals did not recognise that they had a different post operative movement pattern and most were leading an acceptable lifestyle for their needs or wishes. Whether or not the participants felt they had reached their true functional potential after a hip replacement was not explored in this study and should be used as an outcome of any future research. Efficiency of movement or good correlation of repeated gait patterns was not looked at in this study but most THR participants felt they had not reached their full walking potential. Franzen et al (1997) show that although quality of life is at an acceptable level post THR surgery there is still room for improvement and the author suggests that the results of the current study augment this statement.

Pain may have influenced participants reaching their true potential or could be a result of the abnormal movement pattern. 62.5% (n=15) of those with a hip replacement had lumbar spine back pain (modal visual analogue reading of 2 (range 1-3)). Although mild on a 0-10 VAS, this value was very different to the control group where only 1 person (2.4%) had lumbar spine pain VAS=2. A post operation increase in lumbar spine mobility may have played a part in producing this pain however the author does not know specifically when back pain occurred in this participant group. Thurston, (1985) reported back pain in 12 of a group of 20 patients with OA hip who had a simultaneous increase in pelvic movement, whilst Ben Galim et al (2006) report a reduction in pre operative low back pain at 3 months after THR but again the participants had increased pelvic motion. This is different to the findings of the current study but may indicate different spinal movement and pain relationships at the pre and initial post-operative stages to the clinical findings at two years post THR. The longer the time since surgery without adequate rebalancing of hip/ lumbar spine range of motion, soft tissue length and muscle strength the more adapted patients become to their new posture and movement pattern. As reported previously. the findings of Bhave et al (2005) show that soft tissue compensations are present after THR and it can only be hypothesised that these complications increase in magnitude with time.

A number of authors have reported that immediately following THR, the pre-operative referred back pain or pain from increased pelvic movement from adaptation to the painful stiff hip has been relieved by surgery (e.g. Keener et al, 2003; Borstlap et al, 1994). Excessive pelvic or lumbar spine motion during gait has been identified in the pre operation stage (Watelain et al, 2001; Lee et al, 1997; Thurston, 1985), but at the early stages post operative this remains uncorrected, with resulting ongoing altered movement, hip and trunk muscle weakness or learnt habitual patterns of motion (Ben Galim et al, 2006; Oatis, 1990a).

Post operatively a degree of normal hip range returns but the correct pattern of muscle recruitment and strength seen in healthy adults cannot occur due to long term inhibition and atrophy. Therefore a modified gait pattern has to be adopted to allow function. The repetitive walking cycle of the early post operative stages reinforces the abnormal gait pattern and adapted muscle recruitment and in time this becomes the norm or learnt pattern for that individual (Latash & Anson, 1996). However the core stabilisers of the trunk and pelvis may not be recruited in the early stages post operatively or may have become atrophied through misuse during the pre operative painful stages, and hence long term muscle abnormalities have been established. Many authors have reported trunk muscle recruitment to be altered with mechanical low back pain (Silfies et al, 2005; Hodges and Richardson, 1999), hence patients with long term hip/ lumbar spine movement alteration may fall into this category.

By two years post THR, hip movement returns but it is still not to the full range or sequence required to emulate normal walking. Hip muscle strength is also limited (Sicard-Rosenbaum et al, 2000), producing greater alterations to gait mechanics with excessive lumbar spine motion, which may be a result of altered hip movement in combination with poor trunk stabiliser recruitment. By this stage the learnt pattern of movement is now the norm for the individual but it is significantly different to those with no surgery. The altered mechanics put excessive strain on the adjoining motion segments of the knee and pelvis which could combine with poor trunk control to manifest a mechanical cause of low back pain with compensatory increased movement.

Chao et al (1994) suggest that mal-alignment, as defined by alteration in the mechanical axis of the limb, has been shown to alter the stress distribution across joints in the lower extremity which in turn could lead to pain and then wear and tear pathology. Although not a direct comparison because they used patients with non-cemented THR (55 yrs (range 35-85)) Long et al (1993) found significant gains in hip extension between one and two years post surgery but that there was no statistical difference when compared with their pre-operative condition at two years post surgery. Significantly at two years post surgery the operated hip had decreased vertical loading with a 12% difference compared to the non operated side. These authors suggested that reduced loading of the hip at two years post operation confirmed a weakness at the hip muscles regardless of normal stride characteristics and muscle activation.

The findings from the present study concur with those from Long et al (1993) suggesting that clinicians should further promote post operative treatment intervention to reduce the ongoing and longer term biomechanical abnormalities. Following THR surgery patients are not reaching their full movement potential at two years post total hip replacement and develop compensatory patterns which if left untreated could lead to secondary musculoskeletal issues.

Only 50% of the participants in this study had had some form of post operative physiotherapy involving either gait re-education with a walking aid, assessment of stair climbing ability or being given a leaflet with advice and exercises. Only ten percent of these participants had been shown post operative exercises. It may well be that these patients had attended a pre-operative assessment where this information had been given..

From clinical experience and discussion on the Chartered Society of Physiotherapy Orthopaedic discussion pages this limited level of input would appear to be the norm across the UK. Based on the findings from the sample used in this study it is clear that the small amount of formative physiotherapy intervention at the preoperative and initial post operative stages did not allow an adequate return to full movement normality.

Early stage post operative exercise has been shown to assist return of range of movement, muscle strength and function. Gilbey et al (2003) compared results of hip range of movement and hip strength at 3, 12 and 24 weeks after THR in a group of patients following an exercise regime (n=37, age 66.73±10.19yrs) and a control group (n=31, age 63.29±12.01yrs). Patients in the treatment group showed significant gains in range of motion and strength at 12 ($p<0.05$) and 24 weeks ($p<0.01$) compared to the control group. The average cost of the treatment programme was $400 per patient. Further Wang et al (2002) undertaking an identical exercise programme to Gilbey et al (2003) showed that patients (n=15, age 68.3±8.2yrs) also increased their cadence and walking velocity significantly at 12 ($p<0.01$, 0.05 respectively) and 24 ($p<0.05$, 0.05 respectively) weeks post surgery, compared to a control group (n=13, 65.7±8.4 yrs). Unfortunately there were no long term follow up results for these patients..

The only research paper to introduce a randomly allocated specific six week exercise programme with a control group, post THR (Sashika et al, 1996) report significant changes in muscle strength for the operated side ($p<0.01$) and of the non operated side ($p<0.01$) when eccentric muscle activity was introduced. Muscle strength change occurred in the control (no exercise) group over the period of time ($p<0.05$) and there was no explanation for this, however only the treatments groups in this study showed significant changes ($p<0.05$) to walking velocity and cadence. There were only a small number of participants in each group with a very wide time since THR: 6-48 months (mean 26.5 months), therefore it is difficult to say who benefited most from this exercise programme. Therefore these findings cannot be related to all participants with THR.

The findings from Sashika et al are similar to those of Shih et al (1994) with muscle strength continuing to improve until one year post operation. Shih et al report significant increases in hip strength occurring up to one year in women ($p<0.01$) and for men ($p<0.001$) for the hip flexors, extensors and abductors. Murray et al (1975) suggest from their earlier research that the hip abductors do not return to full capacity even at 2 years post THR and that they are still significantly weaker compared to normal healthy values. Assessing patients at later stages Sicard-Rosenbaum et al (2002) assessed 15 people nine months to six years after THR with 15 controls, finding that the operated leg had less muscle strength than the controls, with the hip abductors being most affected. These authors recommended that intervention beyond the initial post surgical rehabilitation is needed to ensure good functional return.

From the literature there would appear to be a body of evidence to support the premise that hip range of movement and muscle strength have the capacity to improve up to two years post surgery following THR. The present study informs this premise by indicating that participants at two years after a THR do not return to the biomechanical and physiological equivalent of their age matched healthy controls and have significant low back pain.

The author proposes that currently hip replacement management regimes are not succeeding in returning the patient to full capacity and that a late stage (6 -12 month) intervention programme should be introduced to assist patients to recover their full functional ability preventing ongoing musculoskeletal problems and back pain.

11.0 CONCLUSIONS

Comparison of 24 age and activity matched individuals at two years following a unilateral total hip replacement (THR) demonstrated statistically significant different joint motion, movement patterns and joint moments to their normal counterparts.

Passive physiological movement was significantly less at the hip joint for the hip replacement group but greater in the lumbar spine which may indicate a compensation pattern, learnt prior to hip surgery, to allow them to function as well as they can with hip joint restriction. The degree of loss of hip movement was significant for the operated side in all movements except extension and medial rotation in 70° of flexion. Hip extension on the operated and non operated sides was extremely limited in the THR group and both these ranges were significantly less than in the control group. The loss of passive physiological movement between the groups, and between the operated and non operated sides is surprising at two years following a THR and indicates that patients do not have the opportunity to enhance their movement from the ranges quoted by other authors at 6-12 months post surgery. The implications of movement reduction may lead to altered movement strategies and abnormal joint loading.

Analysis of dynamic movement patterns through biomechanical testing of the 3-dimensional joint movements and moments augment the findings from the passive physiological data, indicating that hip/ lumbar spine and pelvis/ lumbar spine movements are significantly altered during walking on an even indoor surface. The operated group have increased range of lumbar spine movement in the sagittal and frontal planes during walking and reduced hip motion in all three planes. Pelvic motion is increased in the sagittal plane but remains the same as the non operated group in the other planes. The altered emphasis on lumbar spine motion during walking could lead to damage to the spinal tissues which accommodate to changed load bearing and timing of movement. As 62.5% of the operated group reported lumbar spine pain it is suggested that this could occur as a result of the changed mechanics.

Reduced hip joint moments in the sagittal plane and increased moments in the frontal and horizontal plane demonstrate that the THR group are not as well able to control their hip movement pattern as the non operated control group. The reduction in the sagittal plane moment requires less muscle control at the hip joint but may involve enhanced muscle control either at the lumbar spine or knee to compensate for the reduction in control at the hip. Increased frontal and horizontal plane moments would indicate that the hip joint is being loaded in an altered way and that there would need to be increased hip muscle activity to control movement. Alternatively lumbar spine and knee movement may be changed and this could result in the hip joint moment differences identified here.

This study did not investigate the causes of altered movement or the pre-operative function of the participants but the functional movement results two years after surgery would indicate that recovery is not complete and that the population of people with THR are not able to return to the correct movement ranges and patterns of movement of a non surgical group. A longitudinal study assessing levels of function, pain, activity, and participation would help to determine an appropriate rehabilitation programme for patients following total hip replacement so that they gain full biomechanical recovery.

12.0 REFERENCES

Adams M., Dolan P., Marx C., Hutton W, (1986) An Electrogoniometer Technique for Measuring Lumbar Curvature. *Clin. Biomech.* 1**(3)**: 130 - 134.

Adams M.A. & Dolan P. (1995) Recent advances in lumbar spine mechanics and their clinical significance. *Clin Biomech.* 10**(1)**: 3 - 19.

Ajemian S., Thon D., Kaul L., Clare P., Hughes G. Zernicke R. (1997) Gait Changes Following Total Hip Replacement. *Gait & Posture,* 5**(2)**:146 - 147.

Allard P., Stokes I.A.F., Blanchi J-P. (1995) *Three-dimensional analysis of human movement.* Human Kinetics, Champaign, USA. ISBN 0-87322-623-2.

Alsema R., Deutman R., Mulder T.J. (1994) Stanmore total hip replacement. A 15 to 16 year clinical and radiographic follow up. *J.B.J.S.* 76-B**(2)**: 240 - 244.

American Academy of Orthopaedic Surgeons (1988): *Joint Motion: Method of Measuring and Recording.* Churchill Livingstone, Edinburgh.

Amin A.K., Sales J.D., Brenkel I.J. (2006) Obesity and total knee and hip replacement. *Current Ortho.* 20**(3)**: 216 - 221.

Aminian K., Trevisan C., Najafi B., Dejnabadi H., Frigo C., Pavan E., Telonio A., Cerati F., Marinoni EC., Robert Ph., Leyvraz P-F.(2004) Evaluation of an ambulatory system for gait analysis in hip osteoarthrosis and after total hip replacement. *Gait & Posture,* 20**(1)**: 102 - 107.

Anderson J.A.D. (1982) The thoraco-lumbar spine. *Clin. Rheum. Dis.* 8: 631-653.

Andriacchi T.P., Andersson G.B.J., Fermier R.W, Stern D., Galante J.O. (1980) A study of lower-limb mechanics during stair climbing. *J.B.J.S.* 62-A**(5)**: 749 - 757.

Andriacchi T.P., Galante J.O., Fermier R.W. (1982) The influence of total knee replacement design on walking and stair-climbing. *J.B.J.S.* 64-A**(9)**:1328 - 1335.

Andriacchi T.P. & Strickland A.B. (1983) Gait Analysis as a tool to assess joint kinetics. *Proceedings of NATO: Advanced Study Institute of. Biomechanics of Normal and Pathological Articulating Joints.* Lisbon, Portugal: 83 - 103.

Andriacchi T.P. & Hurwitz D.E. (1997) Gait biomechanics and the evolution of total joint replacement. *Gait & Posture,* 5**(3)**: 256 - 264.

Andriacchi T.P. & Alexander E.J. (2000) Studies of human locomotion: past, present and future. *J Biomech.* 33**(10)**: 1217 - 1224.

Arthritis Research Campaign (ARC) (2003) Statistics fact file. http://www.arc.org.uk/about_arth/astats.htm [Site entered 10.10.2003]

Ateshian G.A., Lai W.M., Zhu W.B. (1994) An asymptotic solution for the contact of two biphasic cartilage layers. *J. Biomech.* 27(11): 1347.

Baker R., Finney L., Orr J. (1999) A new approach to determine the hip rotation profile from clinical gait analysis data. Human Move. Sci. 18(5): 655 - 667.

Barbee Ellison J., Rose S.J., Sahrmann S.A. (1990) Patterns of hip rotation: a comparison between healthy subjects and patients with low back pain. *Phys.Ther.* 70(9): 537 - 541.

Bastian A., Thompson D.M., Bums S.B., Schlegel J.H. (1991) Correlation between lumbar and pelvic movement during normal gait. *Phys. Ther.* 71(6): S92.

Bartlett M.D., Wolf L.S., Shurtleff D.B., Stahell L.T. (1985) Hip flexion contractures: A comparison of measurement methods. *Arch. Phys. Med. Rehabil.* 66(9): 620 - 625.

Beattie P., Issacson K., Riddle D., Rothstein D., (1990) Validity of derived measurements of leg length differences obtained by use of a tape measure. *Phys Ther.* 70(3): 13 – 20.

Benedetti M.G., Catani F., Leardini A., Pignotti E., Giannini S. (1998) Data management in gait analysis for clinical applications *Clin. Biomech.* 13(3): 204 - 215

Ben-Galim P., Ben-Galim T., Rand N., Dekel S., Floman Y. (2006) Hip-Spine Syndrome: The effect of Total Hip Replacement surgery upon low back pain in patients with severe Osteoarthritis of the hip. *The Spine Journal,* 6(5): 31S - 32S

Bell A.L., Brand R.A., Pedersen D.R. (1989). Prediction of hip joint centre location from external landmarks. *Human Move. Sci.* 8(1): 3 - 16.

Bell A.L., Pedersen D.R., Brand R.A. (1990). A comparison of the accuracy of several hip centre location prediction methods. *J.Biomech.* 23(6): 617 - 621.

Bennett D., Ogonda L., Elliott D., Humphreys L., Beverland D.E. (2006) Comparison of gait kinematics in patients receiving minimally invasive and traditional hip replacement surgery: A prospective blinded study. *Gait & Posture* 23(3): 374 - 382.

Benoit D.L., Ramsey D.K., Lamontagne M., Xu L/. Wretenberg P., Renström P. (2006) Effect of skin movement artefact on knee kinematics during gait and cutting motions measured in vivo. *Gait & Posture,* 2(2): 152 - 164.

Bergmann G., Graichen F., Rohlmann A., (1993) Hip joint loading during walking and running measured in two patients. *J Biomech.* 26(8): 969 - 990.

Bergmann G., Deuretzbacher G., Heller M., Graichen F., Rohlmann A., Strauss J., Duda GN. (2001) Hip contact forces and gait patterns from routine activities. *J Biomech.* 34(7): 859 - 71.

Berman A., Quinn R.H., Zarro V.J. (1991) Quantitative gait analysis in unilateral and bilateral total hip replacement. *Arch. Phys. Med. Rehabil.* 72(3): 190 - 194.

Bhave A., Mont M., Tennis S., Nickey M., Starr R., Etienne G. (2005) Functional problems and treatment solutions after total hip and knee joint arthroplasty. *J.B.J.S.,* 87-A **(Suppl. 2)**: 9 - 21.

Biering-Sørensen F. (1984) Physical measurements as risk indicators for low-back pain trouble over a one-year period. *Spine,* 9**(2)**: 106 - 119.

Birrell F., Afzal C., Nahit E., Lunt M., MacFarlane G.J., Cooper C., Croft P.R., Hosie G., Silman A. (2003) Predictors of hip joint replacement in new attenders in primary care with hip pain. *Br. J. Gen. Pract.* 53**(486)**: 26-30.

Bland M. & Altman D. (1986): Statistical Methods for assessing agreement between two methods of clinical measurement. *Lancet,* 327**(8476)**: 307 - 310.

Bogduk N. (1997) *Clinical Anatomy of the lumbar Spine and Sacrum.* 3rd ed. Churchill Livingstone, New York, ISBN 0443060142.

Bogduk N. & Twomey L.T. (1991) *Clinical Anatomy of the Lumbar Spine.* 2nd ed. Churchill Livingstone, UK.

Boocock M.G., Burton A.K., Jackson J., Tillotson K. (1994) Continuous Measurement of Lumbar Posture Using Flexible Electrogoniometers. *Ergonomics,* 37**(1)**:175 - 85.

Borstlap M., Zant J.L., Van Soesbergen M., Van der Korst J.K. (1994) Effects of total hip replacements on quality of life in patients with osteoarthritis and patients with rheumatoid Arthritis. *Clinical Rheum.* 13**(1)**: 45 - 50.

Brand R.A. & Crowninshield R.D. (1980) The effect of cane use on hip contact force. *Clin. Ortho. Rel. Res.* 147: 181 - 184

Brand R.A., Pedersen D.R., Davy D.T., Kotzer G.M., Heiple K.G., Goldberg V.M. (1994) Comparison of hip force calculations and measurements in the same patient. *J. Arthroplasty,* 9**(1)**: 45 - 51.

Brand R.A., Yack H.J. (1996) Effects of leg length discrepancies on the forces at the hip joint. *Clin. Ortho. Rel. Res.* 333: 172 - 180.

British Orthopaedic Association (BOA) (1999) *Total Hip Replacement: A Guide to Best Practice.* British Orthopaedic Association, London, UK.

Britton A.R., Murray D.W., Bulstrode C.J., McPherson K., Denham R.A. (1996) Long-Term Comparison of Charnley and Stanmore Design Total Hip Replacements. *J.B.J.S.* 78-B(5): 802 - 808.

Britton A.R., Murray D.W., Bulstrode C.J., McPherson K., Denham R.A. (1997) Pain levels after total hip replacement. *J.B.J.S.* 79-B(1): 93 - 98.

Buchalter D., Parianpour M., Viola K., Nordin M., Kahanovitz N. (1988) Three-dimensional spinal motion measurements. Part 1: a technique for examining posture and functional spinal motion. *J.Spinal. Disord.* 1(4): 279 - 283.

BUPA (2002) Hospital data (cited in NAO) (2002 – 2003) Hip replacements: an update. Report by the Comptroller and Auditor general, HC956, July.

Burdett R.G., Brown K.E., Fall M.P. (1986) Reliability of four instruments for measuring lumbar spine and pelvic positions. *Phys Ther.* 66: 677 - 684.

Burton A. K. (1986) Regional Lumbar Sagittal Mobility. Measurements with the Flexicurve. *Clin. Biomech.* 1(1): 20 - 26.

Burton A.K. & Tillotson K.M. (1988) Reference values for 'normal' regional lumbar sagittal mobility. *Clin. Biomech.* 3(2): 106 - 113.

Cahalan T.D., Johnston M.E., Liu S., Chao E.Y.S. (1989) Quantitative measurement of hip strength in different age groups. *Clin Orthop.* 246: 136 -145.

Callaghan J.P., Patla A.E., McGill S.M. (1999) Low back three-dimensional joint forces, kinematic and kinetics during walking. *Clin. Biomech.* 14(3): 203 - 216.

Callaghan J.J., Albright J.C., Goetz D.D., Olejniczak J.P., Johnston R.C. (2000) Charnley total hip arthroplasty with cement. Minimum 25 year follow up. *J.B.J.S.* 82-A(4): 487 - 97.

Cappozzo A. (1981) Analysis of the linear displacement of the head and trunk during walking at different speeds. *J Biomech.* 14: 411 - 425.

Cappozzo A. (1984) Gait analysis methodology. *Human Move. Sci.* 3(1-2): 27 - 50.

Carr J.H.& Shepherd R. (1990) A motor learning model for rehabilitation of the movement-disabled. Chapter 1 in Ada L & Canning C. (eds) *Key Issues in Neurological physiotherapy.* Butterworth Heinemann, Oxford.

Centerpulse Orthopaedics (2002)
http://www.centerpulseorthopaedics.com/metasul/story/metasul_story02
[Site entered 10.10.2003]

Chadda D. (2000) PT offers benefit to hip pain patients. *Frontline, Chartered Society of Physiotherapy,* 6(9): 6.

Chao E.Y.S. (1980) Justification of triaxial goniometer for the measurement of joint motion. *J. Biomech.* 13(12): 989 - 1006.

Chao E. & Cahalan T. (1990) Kinetics and kinematics of normal gait. In Schmidt G. (ed) *Gait in Rehabilitation*, pp 45 – 63. Churchill Livingstone, New York.

Chao E.Y.S., Nelahemi E.V.D., Hsu R.W.W., Paley D. (1994) Biomechanics of malalignment. *Orthopedic Clinics of North America,* 25(3): 379 - 386.

Chapman C.R., Casey K.L., Dubner R., Foley K.M., Gracely R.H., Reading A.E. (1985) Pain measurement: an overview. *Pain,* 22: 1 - 31.

Charnley J. (1964) The bonding of prosthesis to bone by cement. *J.B.J.S.* 46-B(3): 518 - 529.

Charnley J. & Kramangar A. (1969) The optimum size of prosthetic heads in relation to the wear of plastic sockets in total hip replacement of the hip. *Med. Biol. Eng.* 7: 31.

Charnley J. (1972) Longterm results of low friction arthroplasty of the hip as a primary intervention. *J.B.J.S.* 54-B(1): 61 - 76.

Charnley J. (1979) *Low friction arthroplasty of the hip: theory and practice.* Springer, New York: p336 – 344.

Charles M.N., Bourne R.B., Davey J.R., Greenwald A.S., Morrey B.F., Rorabeck C.H. (2004) Soft tissue balancing of the hip. *J.B.J.S.* 86-A(5): 1078 - 1088.

Cheng Y., Macera C.A., Davis D.R., Ainsworth B.E., Troped J., Blaw S.N. (2000a) Physical activity and self-reported physician-diagnosed osteoarthritis: is physical activity a factor? *J. Clin. Epidem.* 53(3): 315 - 322.

Cheng P.E., Nicol A.C., Paul J.P. (2000b) Determination of axial rotation angles of limb segments – a new method. *J Biomech.* 33(7): 837 – 843.

Cheng P.E. & Pearcy M. (2001) Graphical presentation of the range of hip and knee rotations for clinical evaluation of gait. *Clin. Biomech.* 16(1): 84 - 86.

Clift B.A., Rowley D.I. (1992) Hip replacement surgery. *Br. J. Hosp. Med.* 47(4): 273 - 279.

Coutts F.J. (1998) Issues regarding the Biometrics Ltd. Twin axis Electrogoniometer. International Conference on Human Motion and Performance: The Interaction between Science and Therapy. University of East London, London UK.

Crosbie J. & Vachalathiti R. (1997) Synchrony of pelvic and hip joint motion during walking. *Gait & Posture,* 6(3): 237 - 248.

Crosbie J., Vachalathiti R., Smith R. (1997a) Patterns of spinal motion during walking. *Gait and Posture,* 5(1): 6 - 12.

Crosbie J., Vachalathiti R., Smith R. (1997b) Age, gender and speed effects on spinal kinematics during walking. *Gait & Posture,* 5(1): 13 - 20.

Crowinshield R.D., Johnston, R.C., Andrews J.G., Brand, R.A. (1977) The effect of joint centre on hip kinetics. *Proc. 23rd Annual ORS Convention* 47-49. Las Vegas, Nevada.

Crowinshield R.D., Brand, R.A., Johnston, R.C. (1978a) The effects of walking velocity and age on hip kinematics and kinetics. *Clin. Ortho. Rel. Res.* 132: 140 - 144.

Crowinshield R.D., Johnston RC., Andrews J.G., Brand, R.A. (1978b) A biomechnical investigation of the human hip. *J. Biomech.* 11(1-2): 75 - 85.

Dandy D.J. & Edwards D.J. (2003) *Essential Orthopaedics and Trauma.* 3rd ed. Churchill Livingston, Oxford, UK. ISBN 0443072132

Davey J.R., O'Connor D.O., Burke D.W., Harris W.H. (1993) Femoral component offset. Its effect on strain in bone-cement. *J Arthroplasty,* 8(1): 23 - 26.

Davis R.B, Õunpnu S., Tyburski D., Gage J.R. (1991) A gait analysis data collection and reduction technique. *Human Move. Sci.* 10(5): 575 - 587.

Day J.W., Smidt G.L., Lehmann T. (1984) Effect of pelvic tilt on standing posture. *Phys. Ther.* 64: 510 - 516.

Delp S.L. & Maloney W. (1993) Effects of hip centre location on the moment generating capacity of the muscles. *J. Biomech.* 26(4/5): 485 - 499.

DeVita P. & Hortobagyi T. (2000) Age causes a redistribution of joint forces and powers during gait. *J. App. Physiology,* 88(5): 1804 - 1811.

Dolan P. & Adams M.A. (1993) The relationship between EMG activity and extensor moment generation in the Erector Spinae muscles during bending and lifting activities. *J. Biomechanics* 26(4/5): 513 - 522.

Dorr L.D., Wan Z., Gruen T. (1997) Functional results in total hip replacement in patients 65 years and older. *Clin. Ortho.* 336: 143 - 51.

Drerup B. & Hierholzer E. (1987) Movement of the human pelvis and displacement of related anatomical landmarks on the body surface. *J. Biomech.* 20: 971 - 977.

Duff-Barclay I., Scales J.T., Wilson J.N. (1966) The development of the Stanmore total hip replacement. *Proc. Royal Soc. Med.* 59: 948 – 951.

Dujardin F., Selva O., Mejjad O., Pasero D., Piraux J.L., Thomine J.M. (1995) Pelvic Motion: individual variations in normal adult gait. *Revue de Chirugie Orthopedique,* 81(7): 592 - 600.

Duncan G.H., Bushnell C., Lavigne J. (1989) Comparison of vertebral and visual analogue scales for measuring the intensity unpleasantness of experimental pain. *Pain,* 37: 295 - 303.

Dvořák J., Vajda E.G., Grob D., Panjabi M.M. (1995) Normal motion of the lumbar spine as related to age and gender. *European Spine Journal,* 4(1): 18 - 23.

Ehara Y., Fujimoto H., Miyazaki S., Tanaka S., Yamamoto S. (1995) Comparison of the performance of three-dimensional camera systems. *Gait & Posture,* 3(3): 166 - 169.

Elftman H. (1939) The function of the arms in walking. *Human Biology,* 11: 529 - 535.

English T.A. (1977) Recording dynamic loads on a femoral hip implant using a telemetric method. *Proceedings of the 1st European Conference on Evaluating Biomaterials,* Strasbourg.

English T.A. & Kilvington M. (1979) In vivo records of hip loads using a femoral implant with telemetric output. *J. Biomed. Engng.* 1: 111-115.

Erhardt K. (1995) Report of joint meeting of the sections of Geriatrics & Gerentology and Rheumatology & Rehabilitation. Osteoarthritis in old age. *J.R. Soc. Med.* 88: 539 - 542.

Espehaug B., Havelin L.I., Engesaeter L.B., Langeland N., Vollset S.E. (1998) Patient satisfaction and function after primary and revision total hip replacement. *Clin. Ortho. Rel. Res.* 351: 135 – 148.

Ethgen O., Bruyere O., Richy F., Dardennes C., Reginster J-Y. (2004) Health related Quality of life in Total Hip and Total knee arthroplasty. *J.B.J.S.* 86-A(5): 963- 974.

Faulkner A., Kennedy L.G., Baxter K., Donovan J., Wilkinson M., Bevan G. (1998) Effectiveness of Hip Prostheses in Primary Total Hip Replacement: A Critical Review of Evidence and an Economic Model. *Health Technology Assessment,* 2(22): 1 – 134.

Fear J., Hillman M., Chamberlain M.A., Tennant A. (1997) Prevalence of hip problems in the population aged 55 years and over: access to specialist care and future demand for hip arthroplasty. *Br. J. Rheum.* 36(1): 74 - 76.

Fender D., Harper W.M., Gregg P.J. (1999) Outcome of Charnley total hip replacement across a single health region in England *J.B.J.S.* 81-B(4): 577 - 581.

Finlay F.R. (1969) Locomotion patterns in elderly women. *Arch. Phys. Med. Rehabil.* 50(**3**): 140 – 148.

Finlay F.R. & Karpovich P. (1964): Electrogoniometer analysis of normal and pathological gait. *The Res. Quart.* 35(**3**): 379 - 384.

Fitzgerald G.K., Wynveen K.J., Rheault W., Rothschild B. (1983). Objective assessment with establishment of normal values for lumbar spine range of motion. *Phys. Ther.* 63(**11**): 1776 - 1781.

Fitzpatrick R., Shortall E., Sculpher M., Murray D., Morris R., Lodge M., Dawson J., Carr A., Britton A., Briggs A. (1998) Primary total hip replacement surgery: a systematic review of outcomes and modelling of cost effectiveness associated with different prostheses. *Health Technology Assessment,* 2(**20**): 1 - 64.

Fortin P.R., Clarke A.E., Joseph L., Liang M.H., Tanser M., Farland D., Phillips C., Partridge A.J., Bélisle P., Fossel A.H., Mohamed N., Sledge C.B., Kat J.N. (1999) Outcomes of total hip and knee replacement: preoperative functional status predicts outcomes at six months after surgery. *Arthritis & Rheumatism,* 42: 1722 - 1728.

Foucher K.C., Hurwitz D.E., Soomekh D., Andriacchi T.P., Rosenberg A.G., Galante J.O. (1998) Factors influencing variations in gait adaptations after total hip replacement. *Gait & Posture,* 7(**2**): 158 - 159.

Foucher K.C., Wimmer M.A., Hurwitz D.E. (2006) The Influence of hip muscle activity on modelled hip contact forces during walking in subjects with total hip replacement. *J Biomech.* 39(**suppl 1**): S44.

Frankel S., Eachus J., Pearson N., Greenwood R., Chan P., Peters T.J., Donovan J., Smith G.D., Dieppe P. (1999) Population requirements for primary hip replacement surgery: a cross sectional study. *The Lancet,* 353(**9161**): 1304 - 1309.

Franzen H., Johnsson R., Nilsson L.T. (1997) Impaired quality of life 10 to 20 years after primary arthroplasty. *J. Arthroplasty,* 12(**1**): 21 - 24.

Frigo C., Crenna P., Jensen L.M. (1996) Moment-angle relationships at lower limb joints during human walking at different velocities. *J. Electromyogr. Kinesiol.* 6(**3**): 177-190.

Garellick G., Malchau H., Herberts P., Hansson E., Axelsson H., Hansson T. (1998a) Life expectancy and cost utility after total hip replacement. *Clin. Ortho. Rel. Res.* 346: 141 - 151.

Garellick G., Malchau H., Herberts P. (1998b) Specific or general health outcomes measures in the evaluation of total hip replacement. A comparison between the Harris Hip Score and the Nottingham Health profile. *J.B.J.S.* 80-B(**4**): 600 - 6.

Gajdosik R.L., Simpson R., Smith R., Dontigny R.L. (1985) Intratester reliability of measuring the standing position and range of motion. *Phys. Ther.* 65(2): 169 - 174.

Gajdosik R.L., Giuliani C.A., Bohammon R.W. (1990) Passive compliance and length of the hamstring muscles of healthy men and women. *Clin.Biomech.* 5(1): 23 - 29.

Gajdosik R.L. (1991) Passive compliance and length of clinically short hamstring muscles of healthy men. *Clin. Biomech.* 6(4): 239 - 244.

Gelber A.C., Hockberg M.C., Mead L.A., Wang N-Y., Wigley F.M., Klag M.J. (1999) Body mass index in young men and the risk of subsequent knee and hip osteoarthritis. *Am. J. Med.* 107(6): 542 - 548.

Gerritsma-Bleeker C.L.E., Deutman R., Mulder Th.J., Steinberg J.D.J. (2000) The Stanmore total hip replacement. *J.B.J.S.* 82-B (1): 97 - 102.

Gilbey H.J., Ackland T.R., Wang A.W., Morton A.R., Trouchet T., Tappen J. (2003) Exercise improves early functional recovery after total hip arthroplasty. *Clin. Ortho.* 408: 193 - 200.

Gill K., Krag M., Johnson G., Haugh L., Pope M. (1988) Repeatability of Four Clinical Methods for Assessment of Lumbar Spinal Motion. *Spine,* 13(1): 50 – 53.

Goldsmith A.A., Dowson D., Wroblewski B.M., Siney P.D., Fleming P.A., Lane J.M., Stone M.H., Walker R. (2001) Comparative study of the activity of total hip arthroplasty patients and normal subjects. *J Arthroplasty,* 16(5): 613 - 9.

Goodwin P.C., Koorts K., Mack R., Mai S., Morrissey M.C., Hooper D.M. (1999) Reliability of leg muscle electromyography in vertical jumping. *Euro. J. App. Phys.* 79: 374 - 78.

Gore D.R., Murray M.P., Sepic S.B., Gardner G.M. (1975) Walking patterns of men with unilateral surgical hip fusion. *J.B.J.S.* 57-A(6): 759 - 765.

Gore T.A., Flynn M., Stevens J. (1979) Measurement and analysis of hip joint movements. *IMechE.* 8(1): 21 – 25.

Gracovetsky S., Kary M., Levy S., Said R.B., Pitchen I., Helie J. (1990) Analysis of spinal and muscular activity during flexion/ extension and free lifts. *Spine,* 15(12): 1333 - 1339.

Griffin A. B., Troup J. D. G., Lloyd D.C E.F. (1984) Test of lifting and handling capacity. Their repeatability and relationship to back symptoms. *Ergonomics,* 27(3): 305 - 320.

Gofton J.P. & Trueman G.E. (1971) Studies in Osteoarthritis of the hip: Part II. Osteoarthritis of the hip and leg-length discrepancy. *Can. Med. Assoc. J.* 104(9): 791-799.

Grood E.S. & Suntay W.J. (1983) A joint coordinate system for the clinical description of three clinical motions: application to the knee. *J. Biomech. Eng.* 105: 136-144.

Gurney B. (2002) Leg length discrepancy. *Gait & Posture,* 15(2): 195 - 206.

Haideri N.F., Halliday S.E., Karol L., Concha C., Smith C., Johnston C. (1997) A Model for the Evaluation of Trunk Motion. *Gait & Posture,* 5(2): 160 - 161.

Hajat S., Fitzpatrick R., Morris R., Reeves B., Rigge M., Williams O., Murray D., Gregg P. (2002) Does waiting for total hip replacement matter? Prospective cohort study. *J. Health Serv. Res. Policy,* 7(1): 19 - 25.

Hall C., Barbee J., Rose S., Sahrmann S.J. (1987) Trends of hip joint range with aging in females. (Abstract) WCPT Abstract R-042 *Phys. Ther.* 67(5): 744.

Hamill J. & Knutzen K.M. (2003) *Biomechanical Basis of Human Movement.* 2nd ed. Lippincot, Williams & Wilkins. Philidelphia.

Hardy R. (1993) Hip replacement in the elderly. *Br. J. Nursing,* 2(1): 57 - 63.

Harris W.H. (1969) Traumatic arthritis of the hip after dislocation and acetabular fractures: Treatment by mold arthroplasty. *J.B.J.S.* 51-A (4): 737 – 55.

Hart D.L. & Rose S. (1986) Reliability of a non- invasive method for measuring the lumbar spine. *J.O.S.P.T.* 8: 180-184.

Health Technology Board for Scotland (2002) Press Release - 14 August, Comment on the use of metal on metal hip resurfacing. http://www.htbs.co.uk/news/pressrel.asp?did=786 [Site entered 10.10.2003]

Heaton J., McMurray R.M., Sloper T., Nettleton S. (2000) Rehabilitation a total hip replacement: patients' perspectives on provision. *Int. J. Rehab. Res.* 23(4): 253 - 259.

Herberts P. & Malchau H. (2000) Longterm registration has improved the quality of hip replacement. A review of the Swedish Total Hip Replacement register comparing 160,000 cases. *Acta. Orthop. Scan.* 71(2): 111 - 121.

Hindle R.J., Pearcy M.J., Gross A.T., Miller D.H.T. (1990) Three-dimensional kinematics of the human back. *Clin. Biomech.* 5(4): 218 - 228.

Hodges P.W. & Richardson C.A., (1999). Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speeds. *Arch. Phys. Med. Rehab.* 80: 1005–1012.

Hooper D.M., Morrissey M.C., Drechsler W.I., Morrissey D., King J.B. (2001) Open and closed kinetic chain exercises in the early period after ACL reconstruction: Improvements in level walking, stair ascent and descent. *Am. J. Sports Med.* 29(2): 167-174.

Hooper D.M., Morrissey M.C., Crookenden R., Beacon J.P. (2002a) Gait adaptations in patients with chronic posterior laxity of the knee. *Clin Biomech.* 17(3): 227-233.

Hooper D.M., Morrissey M.C., Drechsler W.I., Clark N.C., Coutts F.J., McAuliffe T.B. (2002b) Functional assessment of anterior cruciate ligament reconstruction surgery: gait analysis six and twelve months following surgery. *Clin. Ortho. Rel. Res.* 403: 168 - 178.

Hoppenfield S. (1976) Physical examination of the spine and extremities. Appleton - Century - Crofts. Norwalk, Connecticut. USA.

Hoyle D.A., Latour M., Bohannon R.W. (1991) Intraexaminer, interexaminer and interdevice comparability of leg length measurement obtained with measuring tape and metrecom. *J.O.S.P.T.* 14(6): 263 - 268.

Hozack W.J., Rothman R.H., Booth R.E.J., Balderston R.A. (1993) Cemented versus cementless total hip arthroplasty. A comparative study of equivalent patient populations. *Clin. Ortho. Rel. Res.* 289: 161 - 5.

Hulet C., Hurwitz D.E., Andriacchi T.P., Galante J.O., Rosenberg A.G., (1996) Gait Adaptations in Patients with Hip Osteoarthritis. *Gait & Posture,* 4(2): 188.

Hurwitz D.E., Guyton J.A., Andriacchi T.P., Rosenberg A.G. (1992) How canal fill in uncemented total hip replacements affects the biomechanics of gait. *38th Annual Meeting Orthopaedic Research Society.* Chicago: Rider Dickerson 17(1): 281.

Hurwitz D.E., Chertack C.C., Andriacchi T.P. (1993) How gait changes in preoperative and postoperative patients with total hip replacement. *NACOB II proceedings,* 26(3): 325. Abs.

Hurwitz D.E., Hulet C.H., Andriacchi T.P., Rosenberg A.G., Galante J.O. (1997) Gait compensations in patients with osteoarthritis of the hip and their relationship to pain and passive movement. *J. Ortho. Res.* 15(4): 629 - 635.

Jacob H.A.C. & Kissling R.O. (1995). The mobility of the Sacroiliac joints in healthy volunteers between 20 - 50 years of age. *Clin. Biomech.* 10(7): 352 - 361.

James B. & Parker A.W. (1989) Active and passive mobility of lower limb joints in elderly men and women. *Am. J. Phys. Med. Rehab.* 68(4):162 - 167.

James P.J., Nicol A.C., Hamblen D.L. (1994) A comparison of gait symmetry and hip movements in the assessment of patients with monarticular hip arthritis. *Clin. Biomech.* 9(3): 162 - 166.

Jansen E. & Orbaek H. (1980): Reproducibility of Gait Measurement using the Lamoreux Goniometer. *Pros. Orth. Int.* 4: 159 - 161.

Jensen M.P., Karoly P., Braver S. (1986) The measurement of clinical pain intensity: a comparison of 6 methods. *Pain,* 27: 117 - 126.

Johnson F., Osborne J., Allen M., Waugh W. (1982): Continuous Assessment of Knee Function and Patient Mobility. *J.Biomed. Eng.* 4(1): 2 - 8.

Johnston R.C. & Smidt G.L., (1969) Measurement of hip joint motion during walking: Evaluation of an electrogoniometric method. *J.B.J.S.* 51-A(6): 1083 - 1087.

Johnston R.C. & Smidt G.L., (1970) Hip motion measurements during selected activities of daily living. *Clin. Ortho.* 72: 205.

Judge J., Davis R. B., Õunpuu S. (1995) Age-associated Reduction in Step Length: Testing the Importance of Hip and Ankle Kinetics. *Gait & Posture,* 3(2): 81.

Kadaba M.P., Ramakrishnan H.K., Wooten M.E., Gainey J., Gorton G., Cochran G.V.B. (1989). Repeatability of Kinematic, Kinetic and Electromyographic Data in Normal Adult Gait. *J. Ortho. Res.* 7(6): 849 - 860.

Kadaba M.P., Ramakrishnan H.K., Wooten M.E. (1990) Measurement of Lower Extremity Kinematics during level walking. J. Ortho. Res. 8:383-392.

Kapandji I.A. (1989) *The Physiology of the Joints.* Vol. 2, 5th ed. Churchill Livingstone, Edinburgh. ISBN 0443036187.

Kapandji I.A. (1990) *The Physiology of Joints* Vol. 3, 2nd ed. Churchill Livingstone, London. ISBN 0443012091.

Karlson E.W., Mandl L.A., Aweh G.N., Sangha O., Liang M.H., Grodstein F. (2003) Total Hip Replacement due to Osteoarthritis: The importance of Age, Obesity and other modifiable risk factors. *Am. J. Med.* 114(2): 93 - 98.

Karlsson D. & Tranberg R. (1999) On skin movement artefact-resonant frequencies of skin marker attached to the leg. *Human Move. Sci.* 18(5): 627 - 635.

Katz J.N. (2006) Total Joint Replacement in Osteoarthritis. *Best Practice & Res. Clin.Rheum.* 20(1):145 - 153.

Keener J.D., Callaghan J.J., Goetz D.D., Pederson D.R., Sullivan P.M., Johnston R.C. (2003) Twenty-five year results after Charnley total hip arthroplasty in patients less than fifty years old: a concise follow-up of a previous report. *J.B.J.S.* 85-A(6): 1066 - 72.

Kerrigan, D.C., Todd M.K., Della Croce U., Lipsitz, L.A., Collins J.J. (1998) Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments. *Arch. Phys. Med. Rehabil.* 79(3): 317 - 322.

Kerrigan D.C., Lee L., Collins J., O'Riley P., Lipsitz L. (2001a) Reduced Hip extension during healthy elderly and fallers versus young adults. *Arch. Phys. Med. Rehabil.* 82(1): 26 - 30.

Kerrigan D.C., Riley P.O., Lelas J.L., Della Croce U. (2001b) Quantification of pelvic rotation as a determinant of gait. *Arch. Phys. Med. Rehabil.* 82(2): 217 - 220.

Kettlekamp D., Johnson R., Smidt G., Chao E., Walker M. (1970): An Electro-goniometric study of the knee motion in normal gait. *J.B.J.S.* 52-A(4): 775 -790.

Kili S., Wright I., Jones R.S. (2003) Change in Harris hip score in patients on the waiting list for total hip replacement. *Ann. Royal Coll. Surg. Eng.* 85(4): 269 - 271.

Kirkwood R. N., Culham E.G., Costigan P. (1999a) Radiographic and non-invasive determination of the hip joint centre location: effect on hip joint moments. *Clin. Biomech.* 14(4): 227 - 235.

Kirkwood R.N., Culham E.G., Costigan P. (1999b) Hip moments during level walking, stair climbing, and exercise in individuals aged 55 years or older. *Phys. Ther.* 79(4): 360 - 370.

Kirtley C. (1998) Vicon Reliability. http://www.univie.ac.at/cga/faq/reliability/ [Site entered 15.10.2003]

Kirtley C. (2006) *Clinical Gait Analysis: Theory and Practice.* Churchill Livingstone, Edinburgh.

Kirwan J.R., Currey H.L., Freeman M.A., Snow S., Young P.J. (1994) Overall long-term impact of total hip and knee replacement surgery on patients with osteoarthritis and rheumatoid arthritis. *Br. J. Rheum.* 33(4): 357 – 360.

Knutsson S. & Engberg I.B. (1999) An evaluation of patients' quality of life before, 6 weeks and 6 months after total hip replacement. *J. Adv. Nurs.* 30(6):1349 - 59.

Kotzar G.M., Davy D.T., Goldberg V.M., Heiple K.G., Berilla S., Heiple K.G. Jnr., Brown R.H., Burstein A.H. (1991) Telemeterised In vivo hip joint force data: a report on 2 patients after total hip replacement. *J. Ortho. Res.* 9: 621 - 633.

Kotzar G.M., Davy D.T., Berilla J., Goldberg VM. (1995) Torsional loads in early postoperative period following total hip replacement. *J. Ortho. Res.* 13: 945 -955.

Krebs D.E., Edelstein J.E., Fishmans S. (1985) Reliability of observational kinematic gait analysis. *Phys. Ther.* 65(7): 1027 - 1033.

Krebs D.E., Robbins C.E., Lavine L., Mann R.W. (1998) Hip biomechanics during gait. *J.O.S.P.T.* 28(1): 51 - 59.

Krebs D.E., Elbaum L., Riley P.O., Hodge W.A., Mann R.W. (1991) Exercise and gait effects on in vivo contact pressures. *Phys. Ther.* 71: 301 - 309.

Kuno H., Suzuki N., Akataki K., Mita K., Yasubayashi M., Ito M. (1998) Geometrical analysis of hip and knee joint mobility in cerebral palsied children. *Gait & Posture,* 8(2): 110 - 116.

Kuster M., Sakurais S., Wood G.A. (1995) Kinematic and kinetic comparison of downhill and level walking. *Clin. Biomech.* 10(2): 79 - 84.

Kyriazis V. & Rigas C. (2002) Temporal gait analysis of hip osteoarthritic patients operated with cementless hip replacement. *Clin. Biomech.* 17(4): 318 - 321.

Ladin Z. (1995) Three dimensional instrumentation. (Chapter 1) in Allard P., Stokes I.A.F., Blanchi J-P. (1995) *Three-dimensional analysis of human movement.* Human Kinetics, Champaign, USA. ISBN 0-87322-623-2.

Lamoreux L. (1971): Kinematic Measurement in the Study of Human walking. *Bull. Prosth. Res.* 10(15): 3 - 84.

Latash M.L., Anson J.G. (1996) What are "normal movements" in atypical populations? *Behav. Brain Sci.* 19: 55-106

Laubenthal K., Smidt G., Kettlekamp D. (1972): A quantitative analysis of knee motion during activities of daily living. *Phys. Ther.* 52(1): 34 - 42.

Leardini A., Cappozzo A., Catani F., Toksvig-Larsen S., Petitto A., Sforza V., Cassanelli G., Giannini S. (1999) Validation of a functional method for the estimation of hip joint centre location. *J. Biomech.* 32(1): 99 - 103.

Lee, D. (1989) The *Pelvic Girdle. An approach to the examination and treatment of the tumbo-pelvic-hip region.* Churchill Livingstone, UK.

Lee L.W., Kerrigan D.C., Della Croce U. (1997) Dynamic implications of hip flexion contractures. *Am. J. Phys. Med. Rehabil.* 76(6): 502 - 508.

Lee R.Y.W. (2002) Measurement of Movements of the Lumbar Spine. *Physio. Ther. Practice,* 18(4): 159 - 164.

Lee R.Y.W. & Wong T.K.T. (2002) Relationship between the movements of the lumbar spine and hip. *Human Move. Sci.* 21(4): 481 - 494.

Lequesne M.G., Mery C., Samson M., Gerard P. (1987) Indexes of severity for osteoarthritis for the hip and knee. *Scan. J. Rheum.* 65(suppl.): 85 - 89.

Levin U., Nilsson-Wikmar L., Stenström C.H., Lundeberg T. (1998) Reproducibility of manual pressure force on provocation of the sacroiliac joint. *Physio. Res. Int.* 3**(1)**: 1 - 14.

Levine D. & Whittle M.W. (1996) The effect of pelvic movement on lumbar lordosis in the standing posture. *J.O.S.P.T.* 24**(3)**: 130 - 135.

Loebl W.Y. (1967) Measurement of spinal posture and range of spinal movement. *Ann. Phys. Med.* 9: 103 - 110.

Loizeau J., Allard P., Duhaime M., Landler B. (1995) Bilateral gait patterns in subjects fitted with a total hip prosthesis. *Arch. Phys. Med. Rehabil.* 76**(6)**: 552 - 557.

Long W.T., Dorr L.D., Healy B., Perry J. (1993) Functional recovery of non-cemented total hip arthroplasty. *Clin. Ortho.* 288: 73 - 7.

Longjohn D. & Dorr L.D. (1998) Soft Tissue Balance of the Hip. *J. Arthroplasty,* 13**(1)**: 97 -100.

Loslever P. & Barbier F. (1998) Multivariate graphical presentation for gait rehabilitation study. *Gait & Posture,* 7**(1)**: 39 - 44

Lovell F., Rothstein J., Personius W. (1989) Reliability of Clinical Measurements of Lumbar Lordosis Taken with a Flexible Rule. *Phys. Ther.* 69**(2)**: 96 - 103.

Lundberg A. (1996) On the use of bone and skin markers in kinematics research. *Human Move. Sci.* 15(3): 411 - 422.

Mackinnon C.D. & Winter D.A. (1993) Control of whole body balance in the frontal plane during human walking. *J. Biomech.* 26**(6)**: 633 - 644.

MacWilliam C.H., Ulcickas Yood M., Verner J.J., McCarthy B.D., Ward R.E. (1996) Patient -related risk factors that predicted poor outcome after total hip replacement. *Health Services Research,* 31**(5)**: 623 - 639.

Madsen M.S., Ritter M.A., Morris H.H., Meding J.B., Berend M.E., Faris P.M., Vardaxis V.G. (2004) The effect of total hip arthroplasty surgical approach on gait. *J. Ortho. Res.* 22**(1)**: 44 - 50.

Mafiana Nwaobi O. (1986): Electric Goniometer for Positioning Children with Cerebral Palsy. *Phys. Ther.* 66**(10)**: 1540 - 1541.

Mahon J.L., Bourne R.B., Rorabeck C.H., Feeny D.H., Stitt L., Webster-Bogaert S. (2002) Health related quality of life and mobility of patients awaiting elective total hip arthroplasty: a prospective study. *C.M.A.J.* 176**(10)**: 1115 - 1121.

Mallory T.H. (1992) Total hip replacement in the 1990's: The procedure, the patient, the surgeon. *Orthopaedics,* 15**(4)**: 427 - 430.

Mannion A. & Troke M. (1999) A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility. *Clin. Biomech.* 14(**9**): 612 - 619.

Marey E.J. (1873) *Animal mechanism: A treatise on terrestrial and aerial locomotion.* Appleton, New York, USA. Republished as Vol. XI of the International Scientific Series.

Marston R.A., Cobb A.G., Bentley G. (1996) Stanmore compared with Charnley total hip replacement. *J.B.J.S.* 78-B(**2**): 178 - 184.

Mayer R.S., Chen I.H., Lavender S.A., Trafimow J.H., Andersson B.J. (1995) Variance in the measurement of sagittal lumbar spine range of motion among examiners, subjects and instruments. *Spine,* 20(**13**): 1489 - 1493.

MacRae I. & Wright V. (1969) Measurement of Back Movement. *Ann. Rheu. Dis.* **28**: 584 - 589.

McGibbon C.A., Riley P.O., Krebs D.E. (1997) Comparison of hip center estimation using in-vivo and ex-vivo measurements from the same subject. *Clin. Biomech.* 12(**7/8**): 491 - 495.

McGill S.M., Yingling V.R., Peach J.P. (1999) 3-Dimensional kinematic and trunk muscle myoelectric activity in the elderly - a database compared to young people. *Clin. Biomech.* 14(**6**): 389 - 395.

McGregor A.H., McCarthy I.D., Hughes S.P.F. (1995) Motion characteristics of the lumbar spine in the normal population. *Spine,* 20(**22**): 2421 - 2428.

McMurray R.M., Heaton J., Sloper P. Nettleton S. (1999) Measurement of patient perceptions of pain and disability in relation to total hip replacement: the place of the Oxford hip score in mixed methods. *Quality in Health Care,* 8: 228 - 233.

MIE Medical Research Ltd. (2003) Kinemetrix 3-Dimensional Motin Analysis technical specifications: http://www.mie-uk.com/kin/specs.htm
[Site entered 22.10.2003]

Mellin G.P. (1986a) Measurement of thoracolumbar posture and mobility with a Myrin inclinometer. *Spine,* 11(**7**): 759 - 762.

Mellin G.P. (1986b) Accuracy of measuring lateral flexion of the spine with a tape. *Clin. Biomech.* 1(**2**): 85 - 89.

Mellin G. P. (1989) Comparison between tape measurements of forward and lateral flexion of the spine. *Clin. Biomech.* 4(**2**): 121 - 123.

Mellin G.P., Kuski R., Weckstrom, A. (1991) Effects of subject position on measurements of flexion, extension and lateral flexion of the spine. *Spine,* 16: 1108 - 1110.

Menz H.B., Lord S.R., Fitzpatrick R.C. (2003) Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. *Gait & Posture,* 18(1): 35 - 46.

Merritt J., McLean T., Erickson R., Offord K. (1986) Measurement of trunk flexibility in normal subjects: Reproducibility of three clinical methods. *Mayo Clin. Proc.* **61**: 192 -197.

Millar S.A., Mayer T., Cox R., Gatchel P.J., (1992) Reliability problems associated with the modified Schöber technique for the lumbar flexion measurement. *Spine,* 17: 345 - 348.

Minns R.J., Crawford R.J., Porter M.L., Hardinge K. (1993) Muscle strength following total hip arthroplasty. *J. Arthroplasty,* 8(6): 625 - 627.

Moisio K.C., Sumner D.R., Shott S., Hurwitz D.E. (2003) Normalization of joint moments during gait: a comparison of two techniques. *J. Biomech.* 36(4): 599 - 603.

Moll J. & Wright V. (1971) Normal Range of Spinal Mobility- An Objective Clinical Study. *Ann. Rheum. Dis.* **30**: 381 - 386.

Moll J., Liyanage S.P., Wright V. (1972a) An objective clinical method to measure spinal flexion. *Rheum. Phys. Med.* 11(5): 225 - 239.

Moll J., Liyanage S.P., Wright V. (1972b) An objective clinical method to measure spinal extension. *Rheum. Phys. Med.* 11(6): 293 - 312.

Montin L., Suominen T., Leino-Kilpi H. (2002) The experiences of patients undergoing total hip replacements. *J. Ortho. Nursing,* 6: 23 - 29.

Morlock M., Schneider E., Bluhm A., Vollmer M., Bergmann G., Müller V., Honl M. (2001) Duration and frequency of every day activities in total hip patients. *J. Biomech.* 34(7): 873 - 881.

Morrissey M.C., Hooper D.M., Drechsler W.I., Hill H. (2004) Relationship of leg muscle strength and knee function in the early period after anterior cruciate ligament reconstruction. *Scan. J. Med. Sci. Sports,* 14(6): 360 - 366.

Mosekilde L. & Mosekilde L. (1990) Sex Differences in Age- Related Changes in Vertebral Body Size, Density and Biomechanical Competence in Normal Individuals. *Bone,* 11(2): 67 - 73.

Mow V.C. & Ateshian G.A. (1997) Lubrication and wear of diarthrodial joints. In VC Mow & WC Hayes (Eds) Basic Biomechanics (2nd ed.: 275-315). Lippincott-Raven, Philadelphia, USA.

Munin M.C., Kwoh C.K., Glynn N., Gossett L., Rubash H. (1995) Predicting discharge outcome after elective hip and knee arthroplasty. *Am. J. Phys. Med. Rehab.* 74(4): 294 - 301.

Murray D.W., Carr A.J., Bulstrode C.J. (1995a) Which Primary Hip Replacement? *J.B.J.S.* 77-B(4): 520 - 527.

Murray M.P. (1967) Gait as a total pattern of movement, including a bibliography on gait. *Am. J. Phys. Med.* 48: 290 - 330.

Murray M.P., Seireg A., Scholz R.C. (1967) Centre of gravity, centre of pressure and supportive forces during human activities. *J. App. Physiology,* 23(6): 831 - 838.

Murray M.P., Drought A.B., Kory R.C. (1964) Walking patterns of normal men. *J.B.J.S.* 46-A(2): 335 - 360.

Murray M.P, Kory R.C., Clarkson B.H. (1969) Walking Patterns in Healthy Old Men. *J. Geront.* 24: 169 - 178.

Murray M.P., Kory R.C., Sepic S.B. (1970) Walking patterns of normal women. *Arch. Phys. Med. Rehabil.* 51(11): 637 - 650.

Murray M.P., Gore D.G., Clarkson B.H. (1971) Walking patterns of patients with unilateral pain due to Osteoarthrosis and avascular necrosis. *J.B.J.S.* 53-A(2): 259 - 274.

Murray M.P., Brewer B.J., Zuegge R.C. (1972) Kinesiologic measurements of functional performance before and after McKee-Farrar total hip replacement. *J.B.J.S.* 54-A(2): 237 - 256.

Murray M.P., Brewer B.J., Zuegge R.C. (1975) Kinesiology after McKee-Farrar total hip replacement: a two year follow up of one hundred cases. *J.B.J.S.* 57-A(3): 337 - 342.

Murray M.P., Gore D.R., Brewer B.J., Zuegge R.C., (1976) Comparison of functional performance after McKee-Farrar, Charnley and Muller total hip replacement. A six-month follow-up of one hundred sixty-five cases. *Clin. Ortho. Rel. Res.* 121: 33 - 43.

Muybridge E. (1887) Animal location. Reprinted in Brown LS. (ed.) (1957) *Animal in motion.* Dover, New York, USA.

National Audit Office (NAO) (2000) (1999 – 2000) *Hip replacements getting it right first time.* Report by the Comptroller and Auditor general, HC417, April.

National Audit Office (NAO) (2003) (2002 – 2003) *Hip replacements: an update.* Report by the Comptroller and Auditor general, HC956, July.

National Institute for Clinical Excellence (NICE) (2000) *Guidance on the Selection of Prostheses for Primary Total Hip Replacement.* April.

Newton M. & Waddell G. (1991) Reliability and Validity of Clinical Measurement of the Lumbar Spine in Patients with Chronic Low Back Pain. *Physiotherapy,* 77**(12)**: 796 -799.

Nicol A. (1989) Measurement of joint motion. *Clin. Rehabil.* 3: 1 - 9.

Nicol A. (1988): A New Flexible Goniometer with a Widespread Applications.In Biomechanics XB:1029- 1033 Ed. Jonsson B..Human Kinetics Publications, Illinois.

Nilsdotter A.K. & Lohmander L.S., (2002) Age and waiting time as predictor of outcome after total hip replacement for osteoarthritis. *Rheumatology,* 41**(11)**: 1261 - 1267.

Noble P.C., Alexander J.W., Lindahl L.I., Yew D.T., Granberry W.M., Tullos H.T. (1988) The anatomic basis of femoral component design. *Clin. Ortho.* 235: 148 -165.

Nonaka H., Mita K., Watakabe M., Akataki K., Suzuki N., Okuwa T., Yabe K. (2002) Age-related changes in the interactive mobility of the hip and knee joints: a geometrical analysis. *Gait & Posture,* 15(**3**): 236 - 243.

Nordin M. & Frankel V.H. (2001) *Basic Biomechanics of the Musculoskeletal System.* 3rd ed. Lippincot, Williams & Wilkins. Philidelphia.

Norkin C.C. & Levangie P.K. (1992) *Joint Structure and Function: a comprehensive analysis.* 2nd ed. F.A. Davis, Philadelphia.

Norkin C.C. & White D.J. (1995) *Measurement of Joint Motion* 2nd ed. F.A. Davis, Philadelphia.

Norman-Taylor F.H., Palmer C.R., Villar R.N. (1996) Quality of life improvement after hip and knee replacement. *J.B.J.S.* 7-B(**1**): 74 - 7.

Nottrodt J.W., Charteris J., Wall J.C. (1982) The effects of speed on pelvis oscillations in the horizontal plane during level walking. *J.Human Move Studies,* 8: 27 - 40.

O'Connell T., Browne C., Corcoran R., Howell F. (2000) Quality of life following total hip replacement. *Ir. Med. J.* 93(4): 108 - 110.

O'Connor P.D., Robinson M.E., Shirley F.R., MacMillan M.M. (1993) The effect of marker placement deviations on spinal range of motion determined by video analysis. *Phys. Ther.* 73(7): 478 - 483.

Oatis C.A. (1990a) Role of the hip in posture and gait. In Echternach J. (ed) *Clinics in Physical Therapy: Physical Therapy of the Hip,* pp 165 - 179. Churchill Livingstone, New York.

Oatis C.A. (1990b) Biomechanics of the hip. In Echternach J. (ed) *Clinics in Physical Therapy: Physical Therapy of the Hip,* pp 37 - 50. Churchill Livingstone, New York.

Öberg T., Karaszima A., Öberg K. (1993) Basic gait parameters: reference data for normal subjects 10 -79 years of age. *J. Rehab. Res. Develop.* 30(2): 210 - 223.

Ohlen G., Aaro S., Bylund P. (1988): The Sagittal Configuration and Mobility of the Spine in Idiopathic Scoliosis. *Spine,* 13(4): 413 - 416.

Older J. & Buterack R. (1992) Charnley Low Friction Arthroplasty (LFA): A 17 to 21 year follow up study. *J.B.J.S.* 74–B(supp. 3): 251.

Oliver J. & Middleditch A. (1991) *Functional Anatomy of the Spine.* Butterworh Heinemann Ltd., Oxford. ISBN 0750600527.

Olsen V.L., Smidt G.L., Johnston R.C. (1972) The maximum torque generated by the eccentric, isometric and concentric contractions of the hip abductor muscles. *Phys. Ther.* 51: 149 - 158.

Olsson E. (1986) Gait analysis in hip and knee surgery. *Scan. J. Rehab. Med.* Supp. 15: 1-55.

Palastanga N., Fields D., Soames R. (1989) *Anatomy & Human Movement.* Butterworth Heineman Ltd. Oxford.

Paling I.H (2203) Total hip arthroplasty in young patients - can we finally eliminate polyethylene? http://www.corin.co.uk/patient_hip.asp [Site entered 10.10.2003]

Panjabi M.M., Goel V.K., Walters S.D. (1982) Errors in the centre of angle of rotation of a joint: guidelines for an Optimal Experimental Design. *J. Biomech.* 15(7): 537 - 544.

Panjabi M.M. (1992a) The stabilising system of the spine. Part I Function, dysfunction, adaptation and enhancement. *J. Spinal Disorders,* 5(4): 383 - 389.

Panjabi M.M. (1992b) The stabilising system of the spine. Part II Neutral zone and instability hypothesis. *J. Spinal Disorders,* 5(4): 390 - 397.

Paquet N., Malouin F., Richards C.L., Dionne J.P., Comeau F. (1991) Validity and reliability of a new electrogoniometer for the measurement of sagittal dorso-lumbar movements. *Spine,* 16(5): 516 - 519.

Paul J.P. (1967) Forces transmitted by joints in the human body. *Proceedings Institute of mechanical engineers,* V181: 3J, 8 –15.

Paul J.P. (1971) Comparison of EMG signals from leg muscles with the corresponding force actions calculated from walk path measurement. *Human Locomotor Eng.* 48A: 6 - 26.

Paul J.P. & McGrouther D.A. (1975) Forces transmitted at the hip and knee joint of normal and disabled persons during a range of activities. *Acata Ortho Belgica,* 41 **(suppl 1)**: 78 - 88.

Payton O. (1988) *Research: The Validation of Clinical Practice.* Ed. 2
F.A. Davis Co., Philadelphia

Peach J. P., Sutamo C., McGill S. M. (1998) Kinematics and trunk muscle myoelectric activity of the asymptomatic young lumbar spine-A data base. *Arch. Phys. Med. Rehabil.* 79(**6**): 663 - 669.

Pearcy M.J. (1986) Measurement of Back and Spinal Mobility. *Clin. Biomech.*1(**1**): 44 -51.

Pearcy M.J. (1993) Twisting mobility of the human back movement. *Spine,* 18(**1**): 114 - 119.

Pearcy M.J. & Tibrewal S.B. (1984) Axial rotation and lateral bending in the normal lumbar spine measured by three-dimensional radiography. *Spine,* 9(**3**): 582 - 587.

Pearcy M.J., PorteK I., Shepherd J. (1984) Three-dimensional X-ray analysis of normal movement in the lumbar spine. *Spine,* 9(**3**): 294 - 297.

Pearcy M.J., Gill J.M., Whittle M.W., Johnson G.R. (1987) Dynamic back movements measured using a three-dimensional TV System. *J. Biomech.* 20(**10**): 943 - 949.

Pearcy M.J. & Hindle R.J. (1989) New method for the non-invasive three-dimensional measurement of human back movement. . *Clin. Biomech.* 4(**2**): 73 - 79.

Perron M., Malouin F., Moffet H., McFadyen B.J. (2000) Three-dimensional gait analysis with women with a total hip arthoplasty. *Clin. Biomech.* 15(**7**): 504 - 517.

Perry J.A. (1992) *Gait Analysis: Normal and Pathological Function.* Slack Inc., New York.

Perrin T., Dorr L.D., Perry J., Gronley J., Hull D.B. (1985) Functional evaluation of total hip arthroplasty with 5-10 year follow-up evaluation. *Clin. Ortho. Rel. Res.*195: 252 - 260.

Pettine K.A., Amlid B.C., Cabanela M.E. (1991) Elective Total Hip Arthroplasty in patients older than 80 years of age. *Clin. Ortho. Rel. Res.* 266: 127 - 132.

Piazza S.J., Okita N., Cavanagh P.R. (2001) Accuracy of the functional method of hip joint centre location: effects of limited motion and varied implementation. *J. Biomech.* 34(**7**): 967 - 973.

Portek I., Pearcy M.J., Reader G.P., Mowat A.G. (1983) Correlation between radiographic and clinical measurement of lumbar spine movement. *Br.J. Rheum.* 22(**4**): 197 - 205.

Portney L.G. & Watkins M.P. (1993) *Foundations of clinical research: Applications to Practice.* Appleton & Lange. Connecticut, USA.

Pugh L.G. (1973) The oxygen intake and energy cost of walking before and after unilateral hip replacement, with some observation on the use of crutches. *J.B.J.S.* 55-B(**4**): 742 - 745.

Radin E., Paul I., Rose R., Simon S. (1979) *Practical Biomechanics for the Orthopaedic Surgeon.* John Wiley & Sons., New York.

Radin E.L., Burr D.B., Caterson B., Fyhrie D., Brown T.D., Boyd R.D. (1991) Mechanical determinants of osteoarthrosis. *Semin. Arthritis Rheum.* 21(**suppl. 2**): 12 - 21.

Ramakrishnan H.K. & Kadaba M.P. (1991) On the estimation of joint kinematics during gait. *J. Biomech.* 24(**10**): 969 - 977.

Renshaw T.S. (1988) Screening School Children for Scoliosis. *Clin. Ortho. Rel. Res.* 229: 26 - 33.

Reynolds P.M.G. (1975) Measurement of Spinal Mobility: A Comparison of Three Methods. *Rheum. Rehab.* 14: 180 - 185.

Roach K.E. & Miles T.P. (1991) Normal hip and knee active range of motion: the relationship to age. *Phys. Ther.* 71(**9**): 656 - 665.

Roberts W.N., Larson M.G., Liang M.H., Harrison R.A., Barefoot J., Clarke A.K. (1989) Sensitivity of anthropometric techniques for clinical trials in Ankylosing Spondylitis. *Br. J. Rheum.* 28(**1**): 40 - 45.

Röhrle H., Scholten R., Sigolotto C., Sollbach W., Kellner H. (1984) Joint forces in the human pelvis-leg skeleton during walking. *J. Biomech.* 17(**6**): 409 - 424.

Rose M.J. (1991): The Statistical Analysis of the Intra-observer Repeatability of Four Clinical Measurement Techniques. *Physiotherapy,* 77(**2**): 89 - 91.

Rose J. & Gamble J.G. (2006) *Human Walking* 3rd ed. Lippincott Williams & Wilkins, Philadelphia.

Roth P., Unsworth A., Haslock I. (1981): A Discrete Step Goniometer for the Human Elbow. *Eng. in Med.* 10(2): 79 - 83.

Rothman R. & Hozack W. (1988). *Complications of Total Hip Replacements.* W.B. Saunders. Philadelphia.

Rothstein J. (1985) *Measurement in Physical Therapy* Churchill Livingstone, Edinburgh.

Rowe P.J., Nicol A.C., Kelly I.G. (1989) Flexible goniometer computer system for the assessment of hip function. *Clin. Biomech.* 4(2): 68 - 72.

Rowe P.J. & White M. (1996) Three dimensional lumbar spinal kinematics during gait following mild musculo-skeletal low back pain in nurses. *Gait & Posture,* 4(3): 242 - 251.

Royal College of Surgeons & British Orthopaedic Association (2000) *National Total Hip Replacement Outcome Study.* Final report to Department of Health. ISBN 0 902166 98 0.

Rydell N.W. (1966) Forces acting in the femoral head-prosthesis. *Acta Ortho. Scan.* Supp. 88: 37.

Sahrmann S.A. (1987) Muscle imbalances in the orthopaedic and neurological patient. *10th Int. Congress of WCPT Sydney, Australia*: 836 - 841.

Salisbury P. & Porter R. (1987): Measurement of Lumbar Sagittal Mobility A Comparison of Methods. *Spine,* 12(2): 190 - 193.

Salter R.B., Simmonds D.F., Malcolm B.W., Rumble E.J., MacMichael D., Clements N.D. (1980): The Biological Effects of Continuous Passive Motion on the Healing of Full Thickness Defects in Articular Cartilage. *J.B.J.S.* 62-A(8): 1232 - 1251.

Sartor C., Alderink G., Greenwald H., Elders L. (1999) Critical kinematic events occurring in the trunk during walking. *Human Move.Sci.* 18(5): 669 - 679.

Sashika H., Matsuba Y., Watanabe Y. (1996) Home program of physical therapy: effect on disabilities of patients with total hip arthroplasty. *Arch. Phys. Med. Rehabil.* 77: 273-277.

Saunders M., Inman V.T., Eberhart H. (1953) The major determinant of normal and pathological gait. *J.B.J.S.* 35-A(3): 543 - 558.

Scales J.T. & Wilson J.N. (1969) Some aspects of the development of the Stanmore total hip joint prosthesis. *Recon. Surg. Trauma,* 11: 20 - 39.

Schache A.G. & Baker R. (2007) On the expression of joint moments during gait. *Gait & Posture* 25(3): 440 – 452.

Schmalzried T.P., Shepherd E.F., Dorey F. (2000) Wear is a function of use, not time. *Clin. Ortho. Rel. Res.* 381: 36 - 46.

Seidel G.K., Marchinda D.M., Dijkers M., Soutas-Little R.W. (1995) Hip joint centre location from palpable bony landmarks - a cadaveric study. *J. Biomech.* 28(8): 995 - 998.

Shea K.M., Lenhoff M.W., Otis J.C., Backus S.I. (1997) Validation of a method for location of the hip joint centre. *Gait & Posture,* 5(2): 157 - 158.

Shih C-H., Du Y-K., Lin Y-H., Wu C-C. (1994) Muscular recovery around the hip joint after total hip arthroplasty. *Clin. Ortho. Rel. Res.* 302: 115 - 120.

Shimada T. (1996) Factors affecting appearance patterns of hip-flexion contractures and their effects on postural and gait abnormalities. *Kobe J. Med. Sci.* 42: 271 - 290.

Shumway Cook A., Woolacott M. (1995) *Motor Control: Theory and Practical Applications.* Williams & Wilkins, Baltimore, USA.

Sicard-Rosenbaum L., Light K.E., Behrman A,L. (2002) Gait, lower extremity strength and self-assessed mobility after hip arthroplasty. *J. Gerontol. A. Biol Sci. Med. Sci.* 57(1): M47-51.

Siddiqui N.A., Mohandas P., Muirhead-Allwod S., Nuthall T. (2005) (i) A review of minimally invasive hip replacement surgery – current practice and the way forward. *Current Ortho.* 19(4): 247 - 254.

Silfies S.P., Squillante D., Maurer P., Westcott S., Karduna A.R (2005) Trunk muscle recruitment patterns in specific chronic low back pain populations. *Clin. Biomech.* 20 (5): 465–473

Skinner H.B. (1993) Pathokinesiology and total hip arthroplasty. *Clin. Ortho. Rel. Res.* 288: 78 - 85.

Smidt G.L. (1971) Hip motion and related factors in walking. *Phys.Ther.* 51(1): 9-22.

Söderman P., Malchau H., Herberts P. (2001a) Outcome of Total Hip Replacement: a comparison of different measurement methods. *Clin. Ortho. Rel. Res.* 390: 163 - 173.

Söderman P., Malchau H., Herberts P., Zugner R., Regner H., Garellick G. (2001c) Outcome after Total Hip Arthroplasty: Part II Disease specific follow-up and the Swedish National Total Hip Arthroplasty Register. *Acta. Ortho. Scan.* 72 (2): 113 - 119.

Söderman P. & Malchau H., (2001) Is the Harris Hip Score System useful to Study the Outcome of Total Hip Replacements? *Clin. Ortho. Rel. Res.* 384: 189 - 197.

Stagni R., Leardini A., Cappozzo A., Benedetti M.G., Cappello A. (2000) Effects of hip joint centre miscalculation on gait analysis results. *J. Biomech.* 33**(11)**: 1479 - 1487.

Stagni R., Fantozzi S., Cappello A., Leardini A. (2005) Quantification of soft tissue artefact in motion analysis by combining 3D fluoroscopy and sterephotogrammetry: a study on two subjects. *Clin. Biomech.* 20**(3)**: 320 - 329.

Stagni R., Fantozzi S., Cappello A. (2006) Propagation of anatomical landmarks to knee kinematics: Performance of single and double calibration. *Gait & Posture,* 24**(2)**: 137 - 141.

Stanic U., Herman S., Merher J. (1993) Evaluation of rehabilitation of patients with total hip replacements. *IEEE Transactions on Rehabilitation Engineering,* 1**(2)**: 86 - 93.

Stansfield B.W. & Nicol A.C. (1998) Hip joint forces in 40-60 year olds during activities of daily living. *J. Biomech.* 31 **(suppl.1)** July: 162.

Stansfield B.W., Hillman S.J., Hazlewood M.E., Lawson A.A., Mann A.M., Loudon I.R., Robb J.E. (2001) Sagittal joint kinematics, moments and powers are predominantly characterised by speed of progression not age, in normal children. *J. Paed. Ortho.* 21**(3)**: 403 - 411.

Stansfield B.W. & Nicol A.C. (2002) Hip joint contact forces in normal subjects and subjects with total hip prosthesis: walking and stair and ramp negotiation. *Clin. Biomech.* 17**(2)**: 130-139.

Stansfield B.W., Nicol A.C. Paul J.P., Kelly I.G., Graichen F., Bergmann G. (2003) Direct comparison of calculated hip joint contact forces with those measured using instrumented implants. An evaluation of a three-dimensional mathematical model of the lower limb. *J. Biomech.* 36**(2)**: 929 – 936.

Stauffer R.N., Smidt G.L., Wadsworth J.B. (1974) Clinical and biomechanical analysis of gait following Charnley total hip replacement. *Clin. Ortho. Rel. Res.* 99: 70 - 77.

Stokes I.A.F., Bevins T.M., Lunn R.A.(1987) Back surface curvature and measurement of lumbar spinal motion. *Spine,* 12**(4)**: 355 - 361.

Stokes V.P., Andersson C., Forssberg H. (1989) Rotational and translational movement features of the pelvis and thorax during adult locomotion. *J Biomech.* 22**(1)**: 43 - 50.

Sutherland D.H. & Hagy J.L. (1972) Measurement of gait movements from motion picture film. *J.B.J.S..* 54-A**(4)**: 787 - 797.

Syczewska M.G., Öberg T., Karlsson D. (1998) Spine movements during treadmill walking. J. *Biomech.* 31(**1**): 120.

Syczewska M.G., Öberg T., Karlsson D. (1999) Segmental movements of the spine during treadmill walking with normal speed. *Clin. Biomech.* 14(**6**): 384 - 388.

Tata J., Quanbury A., Steinke T., Grahame R. (1978): A Variable axis goniometer for the measurement of single plane movement. J. Biomech. **11**:421-425

Taylor N.F., Evans O.M., Goldie, P.A. (1996) Angular movements of the lumbar spine can reliably measured after 4 minutes of treadmill walking. *Clinical Biomechanics,* 11, 8: 484-486.

Taylor N.F., Goldie P.A., Evans O.M. (1999) Angular movements of the pelvis and lumbar spine during self-selected and slow walking speeds. *Gait & Posture,* 9(**2**): 88 - 94.

Taylor S.J.G., Perry J.S., Meswania J.M., Donaldson N., Walker P.S., Cannon S.R. (1997) Telemetry of forces from proximal femoral replacements and relevance to fixation. *J. Biomech.* 30(**3**): 225 - 234.

Taylor S.J.G., Walker P.S., Perry J.S., Cannon S.R. (1998) The forces in the distal femur and the knee during walking and other activities measured by telemetry. *J. Arthroplasty,* 13(**4**): 428 - 439.

Tetsworth K. & Paley D. (1994) Malalignment and degenerative arthropathy. *Orthopedic Clinics of North America* 25(**3**): 367 - 377.

Thomas K. (2003) Clinical Pathway for Hip and Knee Arthroplasty. *Physiotherapy,* 89(**10**): 603 – 609.

Thornton M.J., Morrissey M.C., Coutts F.J. (1998) Some effects of camera placement on the accuracy of the Kinemetrix 3-D motion analysis system. *Clin. Biomech.* 13(**6**): 452 - 454.

Thurston A.J., Whittle M.W., Stokes I.A.F. (1981) Spinal and pelvic movement during walking - a new method of study. *Eng. In Medicine,* 10(**4**): 219 - 222.

Thurston A.J. & Harris J.D. (1983) Normal Kinematics of the lumbar spine and pelvis. *Spine,* 8(**2**): 199 - 205.

Thurston A.J. (1985) Spinal and pelvic kinematics in osteoarthritis of the hip joint. *Spine,* 10(**5**): 467 - 471.

Tillotson K.M. & Burton A.K. (1991) Non invasive measurement of lumbar sagittal mobility: an assessment of the flexicurve technique. *Spine,* 16(**1**): 29 - 33.

Townsend M., Izak M., Jackson R. (1977): Total Motion Knee Goniometry. *J. Biomech.* 10(3): 183 - 193.

Trew M. & Everett T. (2001) *Human Movement* 4th ed. Churchill Livingstone, Edinburgh.

Troup J.D.G., Hood C.A., Chapman A.E. (1968) Measurement of the sagittal mobility of the lumbar spine and hips. *Ann. Phys. Med.* IX(8): 308 - 321.

Troup J.D.G. (1986): Biomechanics of the Lumbar Spinal Canal. *Clin. Biomech.* 1(1): 31 - 43.

Trudelle-Jackson E., Emerson R., Smith S. (2002) Outcomes of total hip arthroplasty: a study of patients one year post surgery. *J.O.S.P.T.* 32(6): 260 - 267.

Twomey L. (1979) The Effects of Age on the Ranges of Motions of the Lumbar Region. *Aus. J. Physio.* 25(6): 257 - 263.

Twomey L.T. & Taylor J.R. (1983) Sagittal movements of the human lumbar vertebral column: A quantitative study of the role of the posterior vertebral elements. *Arch. Phys. Med. Rehabil.* 64(7): 322 - 325.

Tylkowski C.M., Simon S.R., Mansour J.M. (1982) Internal rotation in gait in spastic cerebral palsy. In J.P Nelson (ed) *The Hip,* Proceedings of the 10th Open Scientific Meeting of the Hip Society. St. Louis: C.V. Mosby: 89 - 125.

University of Leeds, Nuffield Inst. for Health, University of York, National Health Service (NHS) Centre for Review and Dissemination (1996) Total Hip Replacement: *Effective Health Care,* 2(7): 1 - 12.

van den Bogert A.J., Read L., Nigg B.M. (1999) An analysis of hip joint loading during walking, running and skiing. *Med. Sci. Sports,* 31(1): 131 - 142.

van Herp G., Rowe P.J., Salter P.M., Paul J.P (2000) Three dimensional lumbar spine kinematics a study of movement in 100 healthy subjects aged 20 to 60+ years *Rheumatology,* 39(12): 1337 - 1340.

Vanneuville G., Poumarat G., Guillot M., Garcier J.M., Terver S., Duclos F., Vacheron J.J. (1997) Determination of the position of the pelvic girdle using surfsce markers. *Surg. Radiol. Anat.* 19: 341 - 343.

Vogt L., Brettmann K., Pfeifer K., Banzer W. (2003a) Walking patterns of hip arthroplasty patients: some observations on the medio-lateral excursions of the trunk. *Disabil. Rehab.* 25(7): 309 - 17.

Vogt L., Portscher M., Brettmann K., Pfeifer K., Banzer W. (2003b) Cross-validation of marker configurations to measure pelvic kinematics in gait. *Gait & Posture,* 18(3): 178 - 184.

Walker M.L., Rothstein J.M., Finncane S.D., Lamb R.L. (1987) Relationship between lumbar lordosis, pelvic tilt and abdominal muscle performance. *Phys. Ther.* 67(4): 512 - 516.

Wall J., Ashburn A., Klenerman L. (1981) Gait analysis in the assessment of functional performance before and after total hip replacement. *J. Biomed. Eng.* 3: 121 - 127.

Walter S.D. & Panjabi M.M. (1988) Experimental errors in the observation of body joint kinematics. *Technometrics,* 30(1): 71 - 78.

Wang A.W., Gilbey H.J., Ackland T.R. (2002) Perioperative Exercise programs improve early return of ambulatory function after Total Hip Replacement. A randomised controlled trial. *Am. J. Phys. Med. Rehabil.* 81 (11): 801-806.

Watelain E., Barbier F., Allard P., Thevenon A., Angue J-C. (2000) Gait pattern classification of healthy elderly men based on biomechanical data. *Arch. Phys. Med. Rehabil.* 81(5): 579 - 586.

Watelain E., Dujardin F., Babier F., Dubois D., Allard P. (2001) Pelvic and lower limb compensatory actions of subjects in an early stage of hip osteoarthritis. *Arch. Phys. Med. Rehabil.* 82(12): 1705 – 1711.

Waterfield J. & Sim J. (1996) Clinical assessment of pain by the visual analogue scale. *Br. J. Ther. Rehabil.* 3(2): 94 - 97.

Waters R.L. & Mulroy S. (1999) The energy expenditure of normal and pathologic gait. *Gait & Posture,* 9(3): 207 - 231.

Waugh W., Tew M., Johnson F.(1981): Methods of Evaluating Results of Operations for Chronic Arthritis of the Knee. *J. Royal Soc. Med.* 74: 343 - 347.

Weisl H. (1955) The movements of the Sacro-lliac Joint. *Acta Anatomica,* 23: 80.

Whatling G.M., Holt C.A., Jones L., Madete J.K., Dabke H., Alderman P.M., Roberts P. (2006) Investigating the effects of surgical approach on total hip arthroplasty recovery using 3D gait analysis. Zimmer Inc, International Society of Biomechanics, 9th Symposium on 3D analysis of Human Movement, Valenciennes, France.

White T.O. & Dougall T.W. (2002) Arthroplasty of the hip. Leg length is not important. *J.B.J.S.* 85-B (4): 335 - 8.

White A. & Panjabi M. (1976) The Basic Kinematics of the Human Spine. *Spine,* 3(1): 12 - 20.

White A. & Panjabi M. (1978) *Clinical Biomechanics of the Spine.* JB Lippincott Co., Philadelphia.

Whittle M.W. (1996a): *Gait Analysis- An Introduction.* 2^{nd} ed. Butterworth Heinemann, Oxford.

Whittle M.W. (1996b) Clinical Gait Analysis: a review. *Human Move. Sci.* 15(3): 369 - 387.

Whittle M.W. & Levine D.F. (1995) Sagittal plane motion of the lumbar spine during normal gait. *Gait & Posture,* 3(2): 82.

Whittle M.W., Levine D., Burke M. (1998) Three-dimensional motion of the lumbar spine during normal gait. *Gait & Posture,* (Abs.) 7(2): 153.

Whittle M.W. & Levine D. (1999) Three-dimensional relationships between the movements of the pelvis and lumbar spine during normal gait. *Human Move. Sci.* 18(5): 681 - 692.

Williams P., Warwick R., Dyson M., Bannister L. (1989) *Gray's Anatomy* 37th ed. Churchill Livingstone, Edinburgh.

Williams R., Binkley J., Bloch R., Goldsmith C.H., Minuk T. (1993) Reliability of the modified-modified Schöber and double inclinometer methods for measuring lumbar flexion and extension. *Phys. Ther.* 73(1): 26 - 37.

Williamson J.A. & Reckling F. (1978) Limb length discrepancy and related problems following total hip replacement. *Clin. Ortho. Rel. Res.* 134: 135 - 138.

Wilson J.N. & Scales J.T. (1973) The Stanmore metal on metal total hip prosthesis using a three pin type cup. A follow-up of 100 arthroplasties over nine years. *Clin. Ortho.* 95: 239 - 250

Winter D.A. (1983) Biomechanical Motor Patterns in Normal Walking. *J. Motor Behaviour,* 15(4): 302 - 330.

Winter D.A. (1984) Kinematic and kinetic patterns in human gait: variability and compensating effects. *Human Move. Sci.* 3(1-2): 51 - 76.

Winter D.A. (1987) *The Biomechanics and Motor Control of Human Gait.* University of Waterloo Press, Ontario, Canada.

Winter D.A., Patla AE., Frank JS., Walt SE. (1990) Biomechanical Walking Pattern Changes in the Fit and Healthy Elderly. *Phys. Ther.* 70(6): 340 - 347.

Woltring H.J., Huiskes R., de lange A. (1985) Finite centroid and helical axis estimation from noisy landmark measurements in the study of human joint kinematics. *J. Biomech.* 18(5): 379 - 389.

Woltring H.J. (1991) Representation and calculation of three-dimensional joint movement. *Human Move. Sci.* 10(5): 603 - 616.

Woo R.Y.G. & Morrey B.F. (1982) Dislocations after total hip arthroplasty. *J.B.J.S.* 64-A(9): 1295 - 1306.

Wong T.K.T. & Lee R.Y.W. (2004) Effects of low back pain on the relationship between the movement of the lumbar spine and hip. *Human Move. Sci.* 23(1): 21-34.

Woolson S.T., Maloney W.J., Schurman D.J. (1985) Time-realted improvement in the range of motion of the hip after total replacement. *J.B.J.S.* 67-B(8): 1251 - 1254.

Wu G. & Cavanagh P.R. (1995) ISB recommendations for standardisation in the reporting of kinematic data. *J.Biomech.* 28(10): 1257 - 1261.

Wykman A. & Olsson E. (1992) Walking ability after total hip replacement. *J.B.J.S.* 74-B(1): 53 - 56.

Wytch R., Ford D., Ledingham B. (1989) Total joint replacement of the hip. *Therapy Weekly,* March 9: 6 - 7.

Zavadak K.H., Gibson K.R., Whitley D.M., Kwon C.K. (1995) Variability in the attainment of functional milestones during acute care admission after total hip replacement. *J.Rheum.* 22(3): 482 - 487.

Zimmerman S., Hawkes W.G., Hudson J.I., Magaziner J., Hebel J.R., Towheed T., Gardner J., Provenzano G., Kenzora JE. (2002) Outcomes of surgical management of total hip replacement in patients aged 65 years and older: cemented versus cementless femoral components and lateral or anterolateral versus posterior anatomical approach. *J. Ortho. Res.* 20: 182 - 191.

All data in the Appendix are presented in participant order from:
THN 1- 24, THR 1- 24, THRop 1 - 24, or THRnonop 1 - 24.

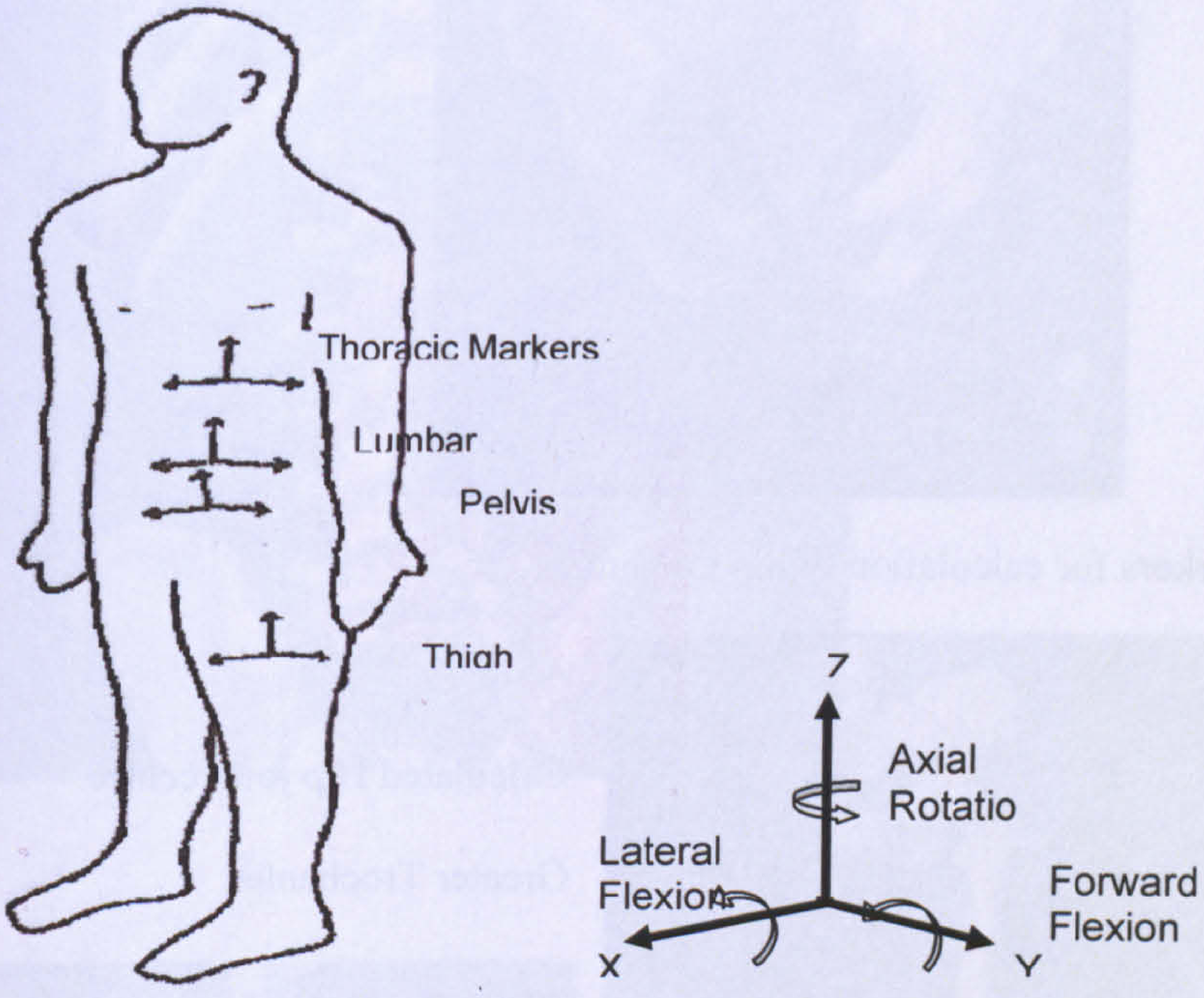
Appendix A: Role of the key players in hip replacement services (NAO, 2003)

National Institute for Clinical Excellence	• Issues relevant guidance on hip prostheses and referral advice
Commission for Health Improvement	• Reviews clinical arrangements in Trusts and monitors the implementation of NICE guidance as part of the reviews
Strategic Health Authorities	• The 'local headquarters' of the NHS • Strategic role to ensure right services are provided in the right place
Primary Care Trusts	• Refer patients to NHS Trusts • Commission services from NHS Trusts and hold the funding
Department of Health	• Manages t he National Joint Registry • Develops appropriate policy • Issues central guidance
Modernisation Agency	• Spreads good practice through the work of the Orthopaedic Services Collaborative and Action on Orthopaedics
NHS Purchasing and Supply Agency	• Centre of expertise for procurement advice • Maintains a database of all prostheses used in the NHS • Offers a prosthesis price benchmarking service to Trusts
Medicines and Healthcare products Regulatory Agency	• Supervises systems for the approval of new prostheses • Collects adverse incident reports from Trusts and manufacturers • Ensures post market surveillance by manufacturers
Manufacturers and suppliers of prostheses	• Develop and test new or amended models, and report problems to the Medicines and Healthcare products Regulatory Agency • Specify whether their prostheses comply with National Institute for Clinical Excellence guidance on Purchasing and Supplies Agency database
NHS Acute Trusts	• Primary responsibility for hip replacement Services
British Orthopaedic Association	• Represents orthopaedic consultants

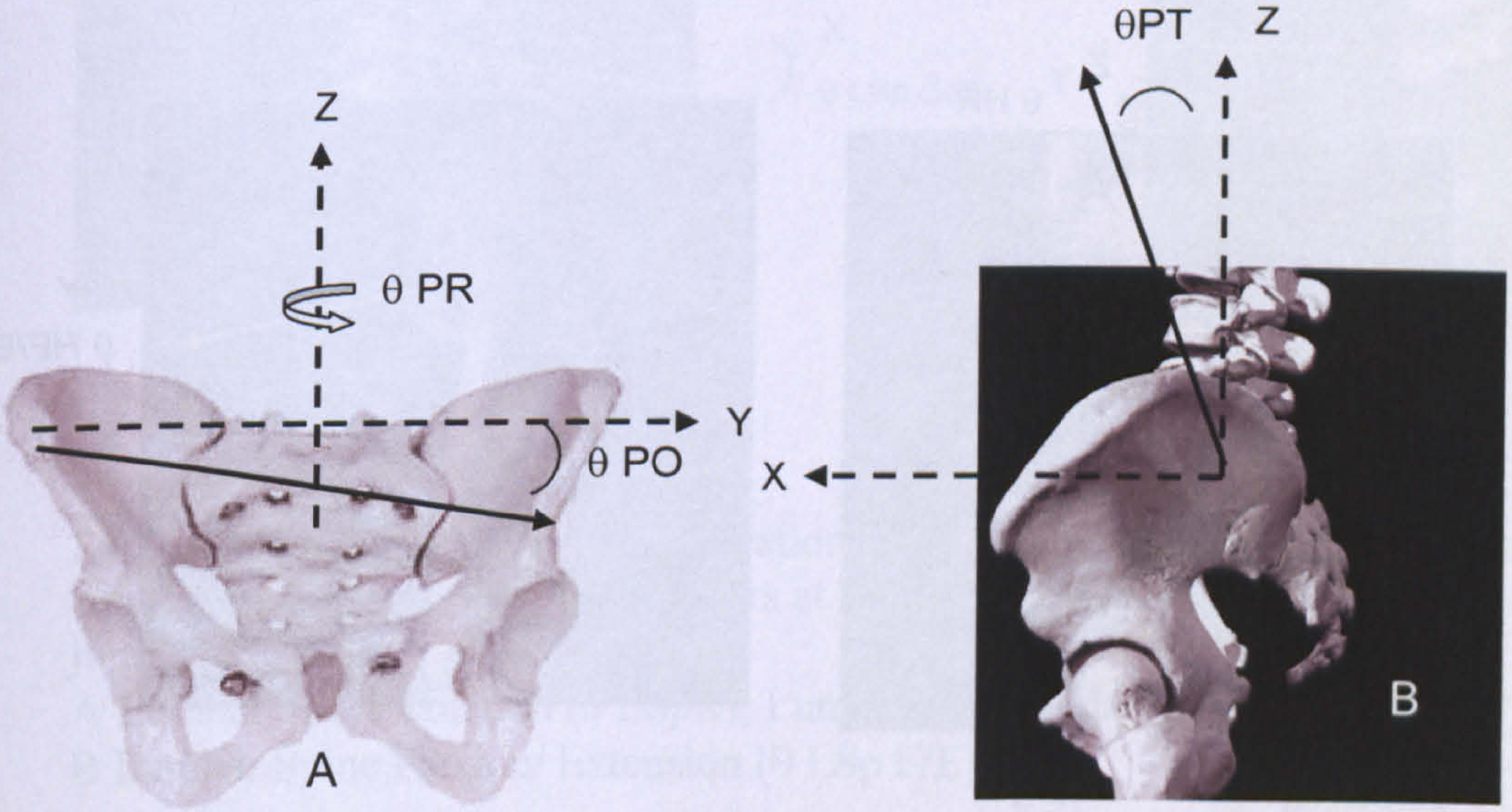
Appendix B: Functional tasks from the Harris Hip Score (Harris, 1969)

	Category	Score
Gait (max 33)		
Limp	A none	11
	B slight	8
	C moderate	5
	D Severe	0
Support	A none	11
	B cane for long walks	7
	C cane most of the time	5
	D one crutch	3
	E two canes	2
	F two crutches	0
	G not able to walk	0
Activities (14 possible)		
Stairs	A normally	4
	B using railing	2
	C in any manner	1
	D unable to do stairs	0
Shoes & socks	A with ease	4
	B with difficulty	2
	C unable	0
Sitting	A any chair one hour	5
	B Highchair half hour	3
	C Unable to sit comfortably	0
Enter public transport		1

Appendix C: ASCII plugin programs for hip and lumbar spine.



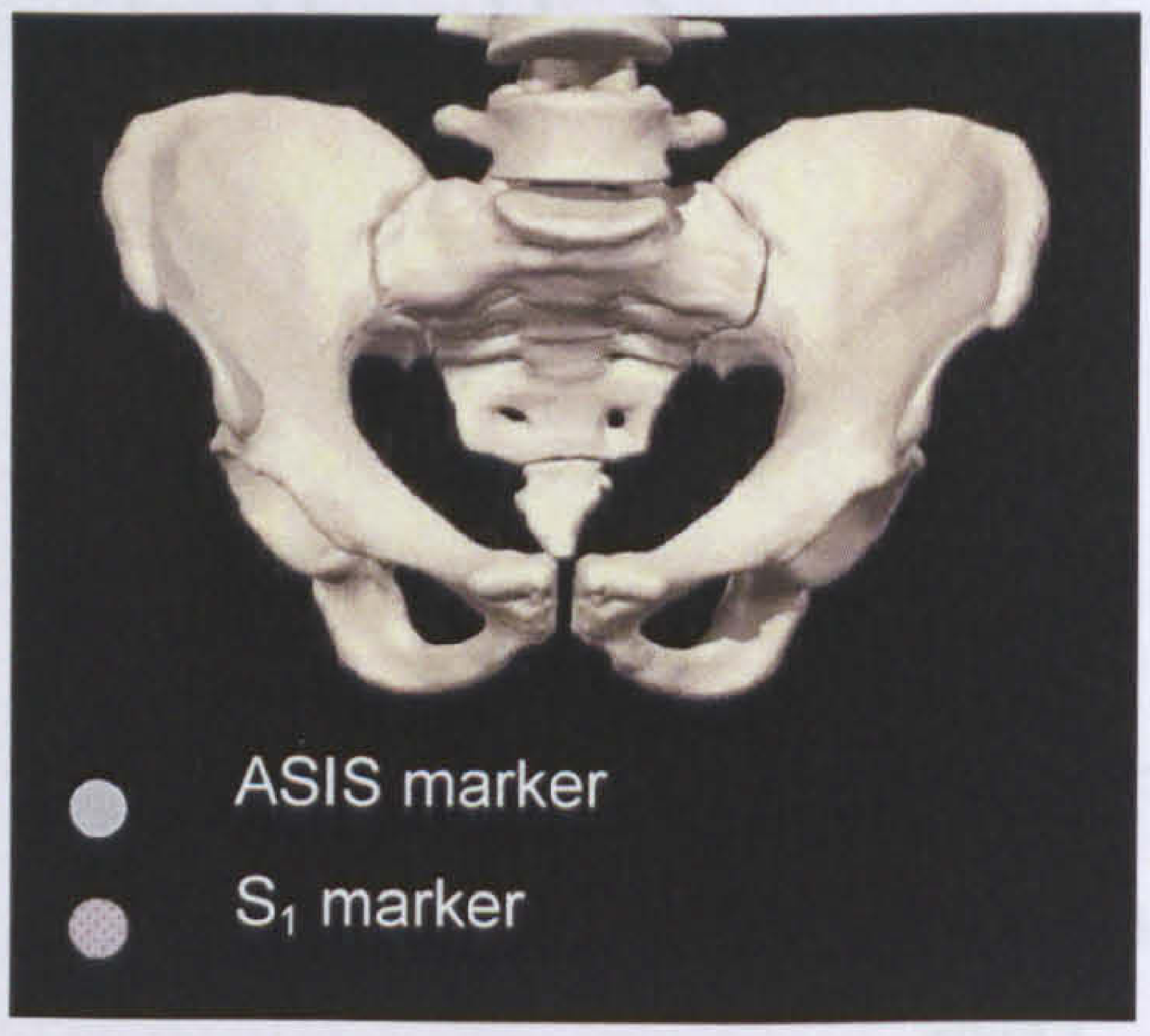
Conventions used for axes and motions for hip and lumbar spine



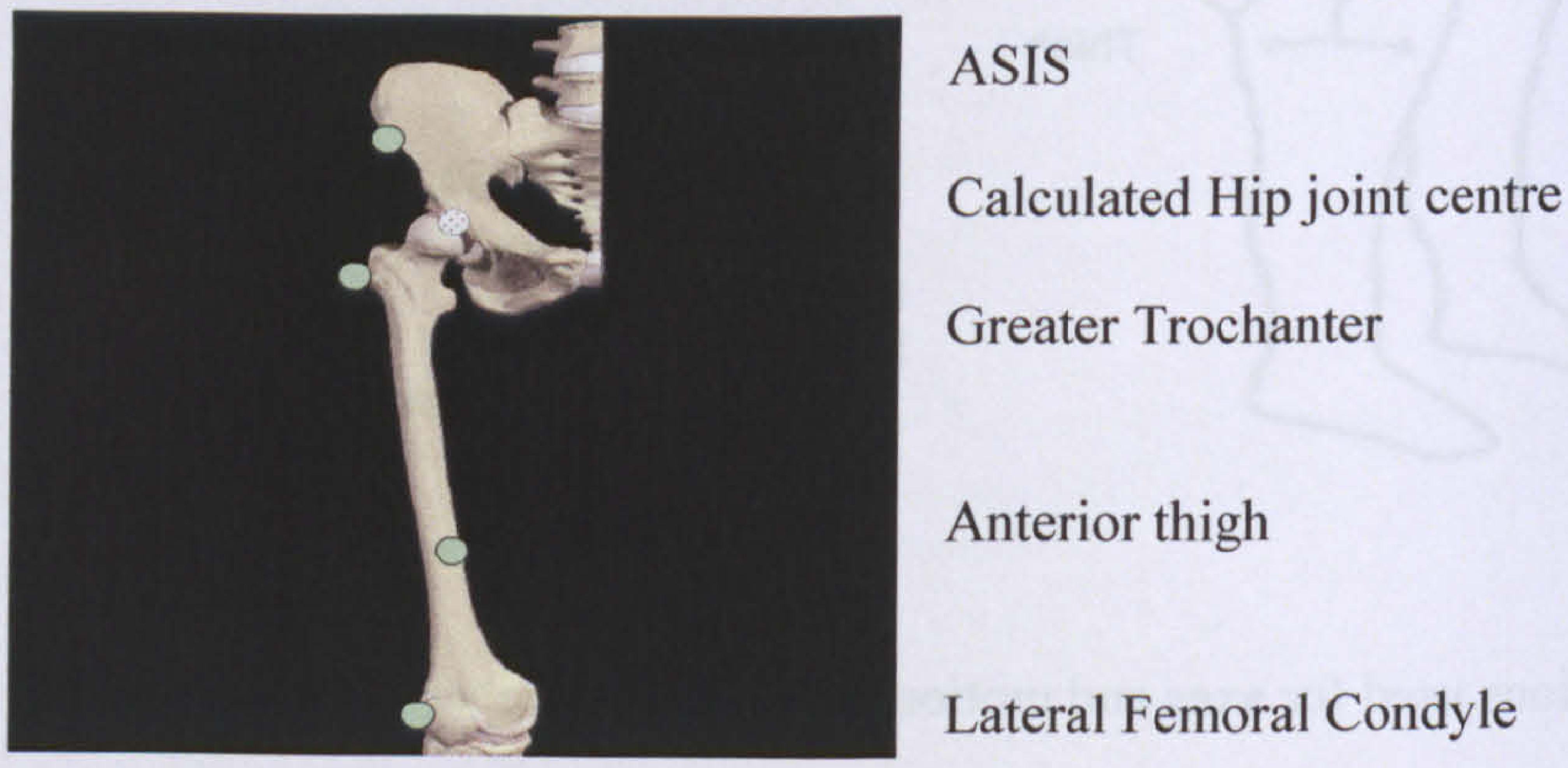
Pelvic angles under consideration: motion of the pelvis was referred to a room-based co-ordinate system.
A Pelvic Rotation (θPR); Pelvic Obliquity (θPO);
B Pelvic Tilt (θPT)

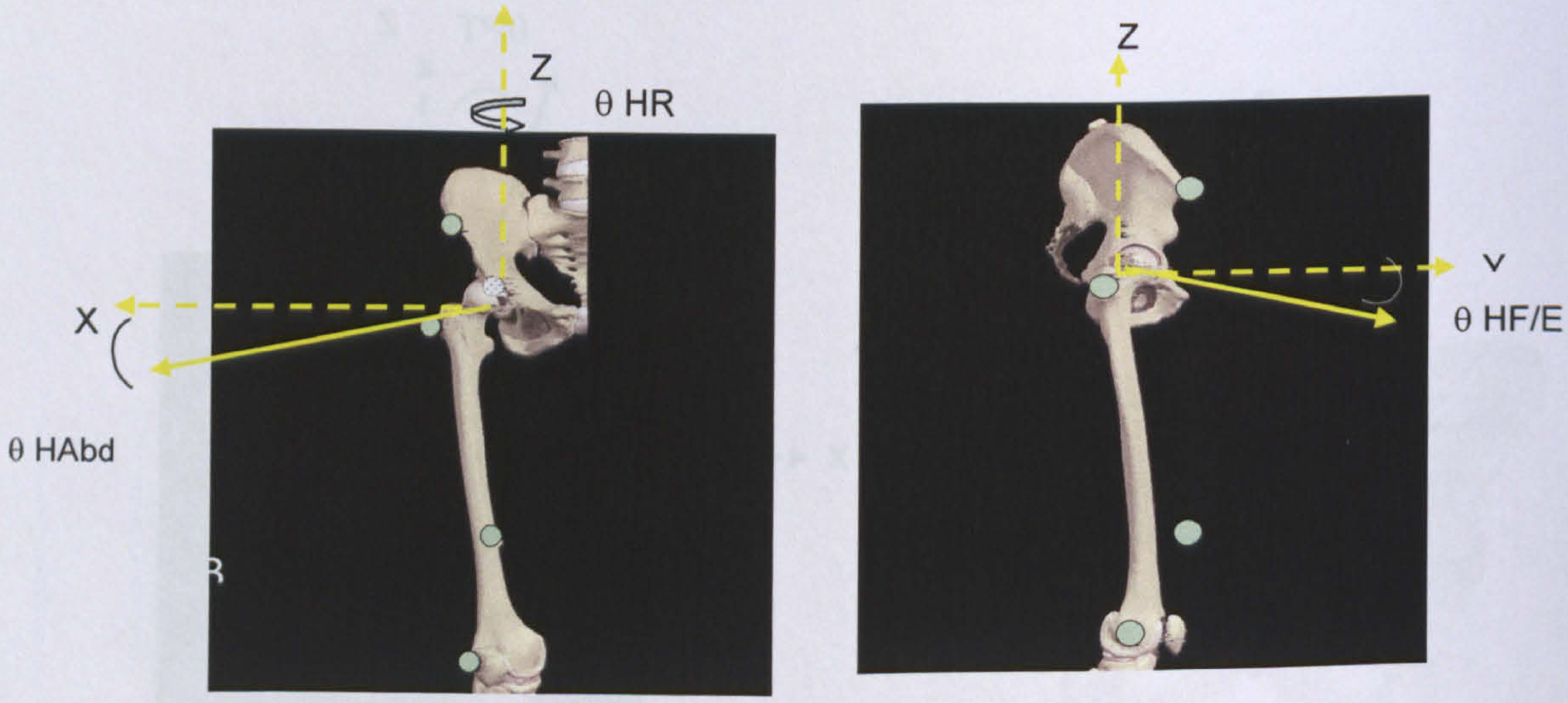
Pictures from Primal Pictures (site accessed 16.02.08)
https://auth.athensams.net/?ath_returl=%22http://www.anatomy.tv/%22&ath_dspid=PRIMAL.atv

Pelvic markers for calculation of hip movement



Thigh markers for calculation of hip movement



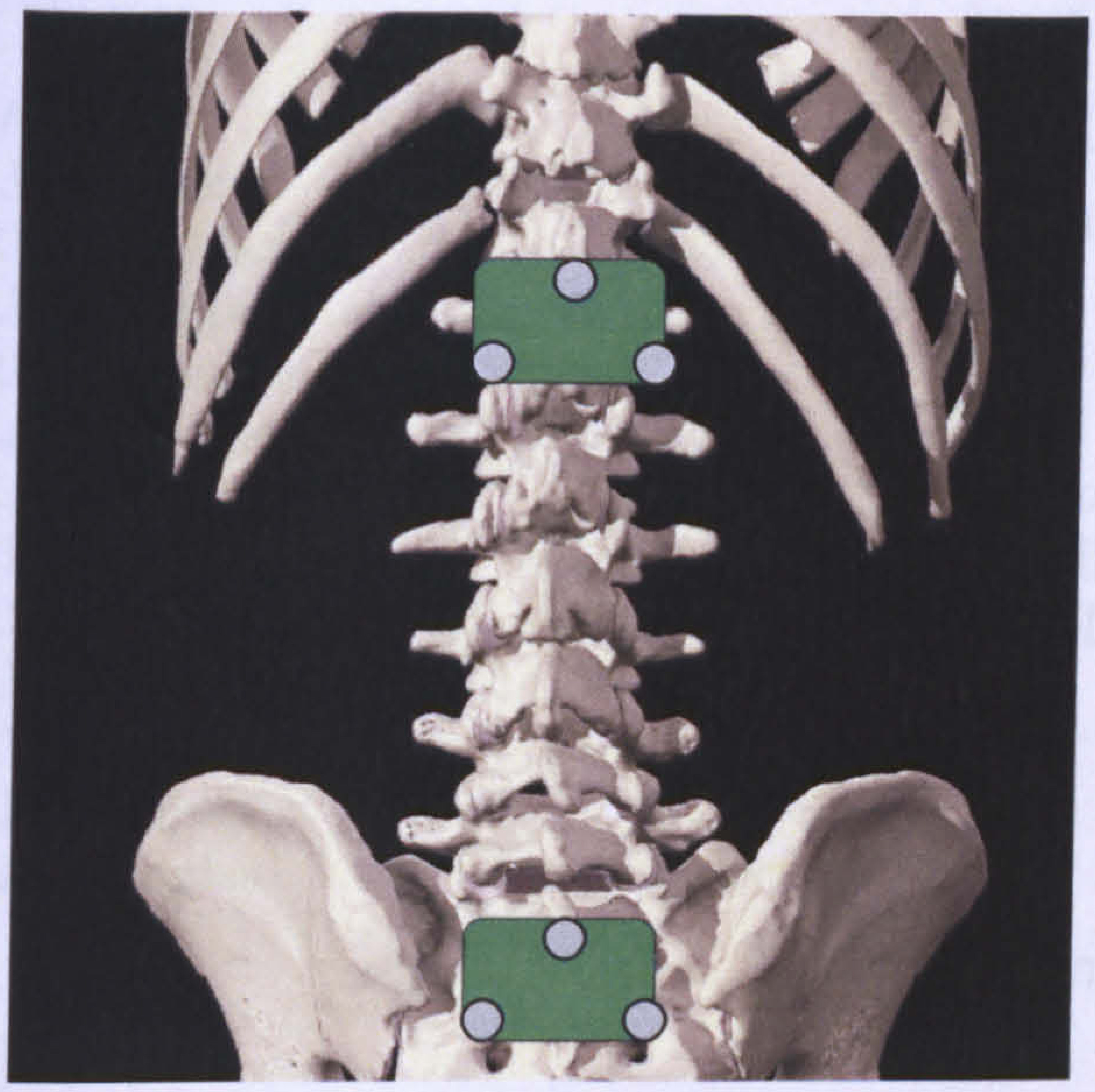


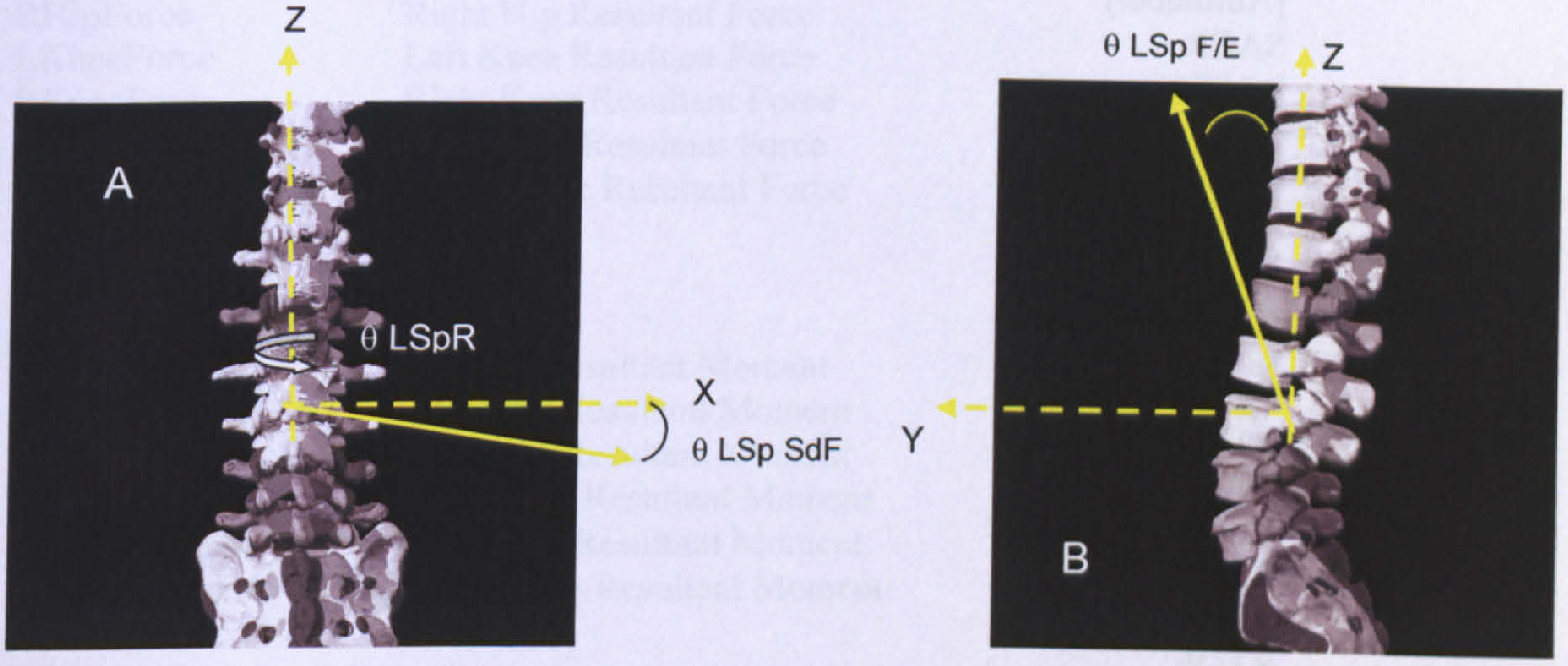
Hip angles under consideration: Angles measured from the identification of the hip joint centre calculated from the position of the markers on the pelvis and then by the relative movement of these markers to the movement of the thigh markers

A Hip Rotation (θ HR) Horizontal Plane; Hip Abduction (θ HAbd) Frontal Plane;

B Hip Flexion/ Extension (θ HF/E) Sagittal Plane

Lumbar Spine markers for calculation of Lumbar spine movement





Lumbar Spine angles under consideration: Angles were derived from the relative change in motion of the three markers at S_2 (pelvis) to those at L_1 (Thoraco-lumbar junction).

A Lumbar Spine Rotation (θ LSpR); Lumbar Spine Side Flexion (θ LSp SdF);

B Lumbar Spine Flexion/ Extension (θ LSp F/E)

(Pictures from Primal Pictures (Site accessed 16.02.08)
https://auth.athensams.net/?ath_returl=%22http://www.anatomy.tv/%22&ath_dspid=PRIMAL.atv)

Appendix C: ASCII plugin programs for hip and lumbar spine.

Hip:

1) Marker identification file,
2) Model parameter file and
3) Hip Model

Lumbar Spine:

1) Marker identification file,
2) Model parameter file and
3) Lumbar Spine Model

Hip:

1) Marker Set Document

```
!MKR#2
[Autolabel]
SACR
LASI
RASI
RGRT
LGRT
LTHI
RTHI
LKNE
RKNE
LTIB
RTIB
LANK
RANK
LTOE
RTOE

Pelvis = LASI,RASI,SACR
LeftUpperLeg = LTHI,LKNE,LGRT
LeftLowerLeg = LKNE,LTIB,LANK
LeftFoot = LANK,LTOE
RightUpperLeg = RTHI,RKNE,RGRT
RightLowerLeg = RKNE,RTIB,RANK
RightFoot = RANK,RTOE

LASI,LGRT
RASI,RGRT

Pelvis,LeftUpperLeg
LeftUpperLeg,LeftLowerLeg
LeftLowerLeg,LeftFoot
Pelvis,RightUpperLeg
RightUpperLeg,RightLowerLeg
```

```
RightLowerLeg,RightFoot

[Angles]
LHipAngles
RHipAngles
LKneeAngles
RKneeAngles
LAnkleAngles
RAnkleAngles
LPelvisRBAngles
RPelvisRBAngles
LPelvisVCMAngles
RPelvisVCMAngles
LFootAngles
RFootAngles

[Forces]
LHipForce          Left Hip Resultant Force
RHipForce          Right Hip Resultant Force
LKneeForce         Left Knee Resultant Force
RKneeForce         Right Knee Resultant Force
LAnkleForce        Left Ankle Resultant Force
RAnkleForce        Right Ankle Resultant Force

[Moments]
LHipMoment         Left Hip Resultant Moment
RHipMoment         Right Hip Resultant Moment
LKneeMoment        Left Knee Resultant Moment
RKneeMoment        Right Knee Resultant Moment
LAnkleMoment       Left Ankle Resultant Moment
RAnkleMoment       Right Ankle Resultant Moment

[Powers]
LHipPower          Left Hip Power
RHipPower          Right Hip Power
LKneePower         Left Knee Power
RKneePower         Right Knee Power
LAnklePower        Left Ankle Power
RAnklePower        Right Ankle Power

[Angular Velocities]
LHipAngVel
RHipAngVel
LKneeAngVel
RKneeAngVel
LAnkleAngVel
RAnkleAngVel
LTimsKneePower     Left Knee Power calculated from Angular velocity
RTimsKneePower     Right Knee Power calculated from Angular velocity
```

```
LAnkleDiff
RAnkleDiff

[Axis Vis]
ORIGINPelvis
AXISXPelvis
AXISYPelvis
AXISZPelvis

ORIGINPelvis,AXISXPelvis
ORIGINPelvis,AXISYPelvis
ORIGINPelvis,AXISZPelvis

ORIGINLFemur
AXISXLFemur
AXISYLFemur
AXISZLFemur

ORIGINLFemur,AXISXLFemur
ORIGINLFemur,AXISYLFemur
ORIGINLFemur,AXISZLFemur

ORIGINRFemur
AXISXRFemur
AXISYRFemur
AXISZRFemur

ORIGINRFemur,AXISXRFemur
ORIGINRFemur,AXISYRFemur
ORIGINRFemur,AXISZRFemur

ORIGINLTibia
AXISXLTibia
AXISYLTibia
AXISZLTibia

ORIGINLTibia,AXISXLTibia
ORIGINLTibia,AXISYLTibia
ORIGINLTibia,AXISZLTibia

ORIGINRTibia
AXISXRTibia
AXISYRTibia
AXISZRTibia

ORIGINRTibia,AXISXRTibia
ORIGINRTibia,AXISYRTibia
ORIGINRTibia,AXISZRTibia

ORIGINLFoot
AXISXLFoot
AXISYLFoot
AXISZLFoot
```

```
ORIGINLFoot,AXISXLFoot
ORIGINLFoot,AXISYLFoot
ORIGINLFoot,AXISZLFoot

ORIGINRFoot
AXISXRFoot
AXISYRFoot
AXISZRFoot

ORIGINRFoot,AXISXRFoot
ORIGINRFoot,AXISYRFoot
ORIGINRFoot,AXISZRFoot
```

2) Model Parameter File

```
{*VICON BodyLanguage (tm) parameter file*}

{*ALL DISTANCE MEASUREMENTS IN millimeters, ALL ANGLES IN degrees*}

{*General Parameters*}
{*==================*}
        $ASISDistance =        0 {* optional - set to zero to use ASIS markers *}
        $MarkerDiameter =      25
        $RKneeWidth =                  0
        $RKneeCircumference =          0
        $LKneeWidth =                  0
        $LKneeCircumference =  0
        $RAnkleWidth =                 0
        $RAnkleCircumference = 0
        $LAnkleWidth =                 0
        $LAnkleCircumference = 0
        $BodyMass =          0 {* kilos *}


{* Variables for the Model *}
{* Change how the model works, but thay are not subject measurements *}
 AngVelHalfPeriod = 2   {* Frames over which to calculate the Angular Velocity *}
 FrameRate = 50    {* Frame rate in Hertz. *}
```

3) Hip Model

```
{*This model uses the Bell et al. (1989) paper to estimate the hip joint centres*}
{*use the BellModel.mkr and Bellmodel.mp files with this model*}
{*Date: 23/05/2003 by Dudley Tabakin*}
{*Modified and extended 28/06/2004 by Timothy Pitt, Vaquita Software *}

Macro AXISVISUALISATION(Segment)
        ORIGIN#Segment=0(Segment)
```

```
        AXISX#Segment={100,0,0}*Segment
        AXISY#Segment={0,100,0}*Segment
        AXISZ#Segment={0,0,100}*Segment
        output(ORIGIN#Segment,AXISX#Segment,AXISY#Segment,AXISZ#Segment)
Endmacro

macro CALCULATEWIDTH( Joint )
        if Joint#Width == 0 then
          Joint#Width = Joint#Circumference / 3.14
          PARAM( Joint#Width )
        endif
endmacro

Macro ANGULARVELOCITY( Seg1, Seg2, Joint, LeftSide )
  Seg1Att = ATTITUDE( Seg1 )
  XAV = COMP( {0,1,0}*Seg1Att[AngVelHalfPeriod], {0,0,1}*Seg1Att[-
AngVelHalfPeriod] )
  YAV = COMP( {0,0,1}*Seg1Att[AngVelHalfPeriod], {1,0,0}*Seg1Att[-
AngVelHalfPeriod] )
  ZAV = COMP( {1,0,0}*Seg1Att[AngVelHalfPeriod], {0,1,0}*Seg1Att[-
AngVelHalfPeriod] )
  {* combine and convert to global axes *}
  Seg1#AV = {XAV,YAV,ZAV} * Seg1Att

  Seg2Att = ATTITUDE( Seg2 )
  XAV = COMP( {0,1,0}*Seg2Att[AngVelHalfPeriod], {0,0,1}*Seg2Att[-
AngVelHalfPeriod] )
  YAV = COMP( {0,0,1}*Seg2Att[AngVelHalfPeriod], {1,0,0}*Seg2Att[-
AngVelHalfPeriod] )
  ZAV = COMP( {1,0,0}*Seg2Att[AngVelHalfPeriod], {0,1,0}*Seg2Att[-
AngVelHalfPeriod] )
  {* combine and convert to global axes *}
  Seg2#AV = {XAV,YAV,ZAV} * Seg2Att

  {* scale by the time factor *}
  Seg1#Seg2#AV = (Seg1#AV - Seg2#AV) * FrameRate / (2*AngVelHalfPeriod)

  {* Output, tweaking order to match joint angle conventions *}
  Joint#AngVel = { Seg1#Seg2#AV(2), Seg1#Seg2#AV(1), Seg1#Seg2#AV(3) }
  if LeftSide==0 then
    Joint#AngVel = Joint#AngVel(-2)(-3)
  endif
EndMacro


{*=========================*}
{* Either left or right leg markers may be missing *}
{* if imported from the kinemetrix system *}
OPTIONALPOINTS( RGRT, RTHI, RKNE, RTIB, RANK, RTOE )
OPTIONALPOINTS( LGRT, LTHI, LKNE, LTIB, LANK, LTOE )

{*=========================*}
{* Calculate Joint widths if needed *}
```

```
CALCULATEWIDTH ( $RKnee )
CALCULATEWIDTH ( $LKnee )
CALCULATEWIDTH ( $RAnkle )
CALCULATEWIDTH ( $LAnkle )


{*========================*}
{*== Segments ============*}

{*== Pelvis Segment=======*}

MASI = (LASI+RASI)/2

Pelvis = [MASI,LASI-RASI,MASI-SACR,yzx]

AXISVISUALISATION(Pelvis)


$ASISAlternate = AVERAGE( DIST(LASI,RASI) )

If $ASISDistance == 0
        $ASISDistance = $ASISAlternate
EndIf
PARAM( $ASISDistance )

{*Right and Left Hip Joint Centres*}

BellR = {0,0.14*$ASISDistance,-0.3*$ASISDistance}
BellL = {0,-0.14*$ASISDistance,-0.3*$ASISDistance}
RHJC = RASI + BellR*ATTITUDE(Pelvis)
LHJC = LASI + BellL*ATTITUDE(Pelvis)
Output (RHJC,LHJC)


{*== Femur Segments =======*}

MRTHI = PERP(RTHI,RGRT,RKNE)
MLTHI = PERP(LTHI,LGRT,LKNE)

REFRTHI = MRTHI + NORM(RGRT,RTHI,RKNE)*DIST(RTHI,MRTHI)
REFLTHI = MITHI + NORM(LKNE,LTHI,LGRT)*DIST(LTHI,MLTHI)

OUTPUT(MRTHI,MLTHI,REFRTHI,REFLTHI)

RFemur = [RKNE,RGRT-RKNE,REFRTHI-RTHI,zyx]
LFemur = [LKNE,LGRT-LKNE,REFLTHI-LTHI,zyx]

{*Calculate Right and Left Knee Joint Centres and reposition the origin of the Thigh
segments at these centres*}

RKJC = RKNE + {0,0.5*($MarkerDiameter+$RKneeWidth),0}*Attitude(RFemur)
LKJC = LKNE - {0,0.5*($MarkerDiameter+$LKneeWidth),0}*Attitude(LFemur)
```

```
RFemur = RKJC+Attitude(RFemur)
LFemur = LKJC+Attitude(LFemur)

AXISVISUALISATION(RFemur)
AXISVISUALISATION(LFemur)


{*== Tibia segments ========*}

MRTIB = PERP(RTIB,RANK,RKNE)
MLTIB = PERP(LTIB,LANK,LKNE)

REFRTIB = MRTIB + NORM(RKNE,RTIB,RANK)*DIST(RTIB,MRTIB)
REFLTIB = MLTIB + NORM(LANK,LTIB,LKNE)*DIST(LTIB,MLTIB)

OUTPUT(MRTIB,MLTIB,REFRTIB,REFLTIB)

RTibia = [RANK,RKNE-RANK,REFRTIB-RTIB,zyx]
LTibia = [LANK,LKNE-LANK,REFLTIB-LTIB,zyx]

{*Calculate Right and Left Ankle Joint Centres *}

RAJC = RANK + {0,0.5*($MarkerDiameter+$RAnkleWidth),0}*Attitude(RTibia)
LAJC = LANK - {0,0.5*($MarkerDiameter+$LAnkleWidth),0}*Attitude(LTibia)

{*Reposition the origin of the Tibia segments at these centres*}

RTibia = RAJC+Attitude(RTibia)
LTibia = LAJC+Attitude(LTibia)

AXISVISUALISATION(RTibia)
AXISVISUALISATION(LTibia)


{*== Foot Segments ========*}

{* N.B. These are not the same as VCM/PlugIn Gait *}
{* These ones assume Z up in the neutral position *}
{* rather than Z along the long axis of the foot *}

RFoot = [RAJC,RTOE-RAJC,-2(RTibia),xzy]
LFoot = [LAJC,LTOE-LAJC,-2(LTibia),xzy]

AXISVISUALISATION(RFoot)
AXISVISUALISATION(LFoot)


{*========================*}
{*== Angles ===============*}

LHipAngles = <Pelvis,LFemur,yxz>
RHipAngles = -<Pelvis,RFemur,yxz>(-1)
```

```
LKneeAngles = <LFemur,LTibia,yxz>(-1)
RKneeAngles = -<RFemur,RTibia,yxz>

{* N.B. These ankle angles are not the same as VCM/PlugIn Gait *}
{* due to the difference in the way the foot segments are modelled *}
LAnkleAngles = <LTibia,LFoot,yxz>
RAnkleAngles = -<RTibia,RFoot,yxz>(-1)

OUTPUT( LHipAngles, RHipAngles )
OUTPUT( LKneeAngles, RKneeAngles, LAnkleAngles, RAnkleAngles )


{* Progression direction of the subject *}

{* Use either the movement of the SACR, *}
{* or the mean direction of the pelvis *}
Direction = AVERAGE( SACR[10] - SACR[-10] )
PelvDirection = AVERAGE( -MASI + SACR )

if DIST(Direction,{0,0,0}) < 50 then
  Direction = PelvDirection
endif

{* Find the closest global axis *}
Direction = Direction/DIST( Direction,{0,0,0} )
XDist = COMP( Direction, {1,0,0} )
YDist = COMP( Direction, {0,1,0} )

if XDist < 0 then
  XDist = -XDist
  XBack = -1
else
  XBack = 1
endif

if YDist < 0 then
  YDist = -YDist
  YBack = -1
else
  YBack = 1
endif

{* define the frame of reference *}
if XDist > YDist
  ProgressFrame = [ {0,0,0}, XBack*{1,0,0}, {0,0,1}, xyz ]
else
  ProgressFrame = [ {0,0,0}, YBack*{0,1,0}, {0,0,1}, xyz ]
endif

{* Pelvis  Progression(VCM)*}
RPelvisVCMAngles = -<ProgressFrame ,Pelvis,yxz>(-2)
LPelvisVCMAngles = -RPelvisVCMAngles(-1)
```

```
{* Pelvis  Progression(RB-style)*}
RPelvisRBAngles = -<ProgressFrame ,Pelvis,zxy>(-2)
RPelvisRBAngles = < RPelvisRBAngles(3), RPelvisRBAngles(2), RPelvisRBAngles(1) >
LPelvisRBAngles = -RPelvisRBAngles(-1)

{*Foot Progression *}
LFootAngles = -<ProgressFrame ,LFoot,yxz>(-2)
RFootAngles = -<ProgressFrame ,RFoot,yxz>(-3)

OUTPUT( LPelvisRBAngles, RPelvisRBAngles, LPelvisVCMAngles,
RPelvisVCMAngles)
OUTPUT( LFootAngles, RFootAngles  )



{*========*}
{*Kinetics*}
{*========*}

AnthropometricData
AnthroFemur 0.1 0.567 0.323 0
AnthroTibia 0.0465 0.567 0.302 0
AnthroFoot 0.0145 0.5 0.475 0
EndAnthropometricData


Pelvis = [Pelvis,0.142*$BodyMass,{0,0,0},{0,0,0}]

LFemur = [LFemur,Pelvis,LHJC, AnthroFemur]
RFemur = [RFemur,Pelvis,RHJC, AnthroFemur]

LTibia = [LTibia,LFemur,LKJC,AnthroTibia]
RTibia = [RTibia,RFemur,RKJC,AnthroTibia]

LFoot = [LFoot,LTibia,LAJC,AnthroFoot]
RFoot = [RFoot,RTibia,RAJC,AnthroFoot]


If $BodyMass <> 0 AND $Static <> 1 Then

{*Decompose Reactions, Mormalise, Adjust Polarities, Recompose, Re-decompose!*}
{*=====================================================================
============*}
NN = $BodyMass

LHF = 1(REACTION(LFemur))/NN
LHF = {1(LHF),2(LHF),-3(LHF)}
LHM = 2(REACTION(LFemur))/NN
LFemurR = |LHF,LHM,3(REACTION(LFemur))|
LHipForce = 1(LFemurR)
LHipMoment = 2(LFemurR)
```

```
RHF = 1(REACTION(RFemur))/NN
RHF = {1(RHF),-2(RHF),-3(RHF)}
RHM = 2(REACTION(RFemur))/NN
RHM = {-1(RHM),2(RHM),-3(RHM)}
RFemurR = |RHF,RHM,3(REACTION(RFemur))|
RHipForce = 1(RFemurR)
RHipMoment = 2(RFemurR)

LKF = 1(REACTION(LTibia))/NN
LKF = {1(LKF),2(LKF),-3(LKF)}
LKM = 2(REACTION(LTibia))/NN
LKM = {1(LKM),-2(LKM),3(LKM)}
LTibiaR = |LKF,LKM,3(REACTION(LTibia))|
LKneeForce = 1(LTibiaR)
LKneeMoment = 2(LTibiaR)

RKF = 1(REACTION(RTibia))/NN
RKF = {1(RKF),-2(RKF),-3(RKF)}
RKM = -2(REACTION(RTibia))/NN
RTibiaR = |RKF,RKM,3(REACTION(RTibia))|
RKneeForce = 1(RTibiaR)
RKneeMoment = 2(RTibiaR)

LAF = 1(REACTION(LFoot))/NN
LAF = {-3(LAF),2(LAF),-1(LAF)}
LAM = 2(REACTION(LFoot))/NN
LFootR = |LAF,LAM,3(REACTION(LFoot))|
LAnkleForce = 1(LFootR)
LAnkleMoment = 2(LFootR)

RAF = -1(REACTION(RFoot))/NN
RAF = {3(RAF),2(RAF),1(RAF)}
RAM = 2(REACTION(RFoot))/NN
RAM = {-1(RAM),2(RAM),-3(RAM)}
RFootR = |RAF,RAM,3(REACTION(RFoot))|
RAnkleForce = 1(RFootR)
RAnkleMoment = 2(RFootR)

OUTPUT(LHipForce,RHipForce,LKneeForce,RKneeForce,LAnkleForce,RAnkleForce)
OUTPUT(LHipMoment,RHipMoment,LKneeMoment,RKneeMoment,LAnkleMoment,RA
nkleMoment)

{*Joint Powers (W/kg)*}
{*==================*}
LHipPower =  POWER( Pelvis, LFemur )/NN
RHipPower =  POWER( Pelvis, RFemur )/NN
LKneePower = POWER( LFemur, LTibia )/NN
RKneePower = POWER( RFemur, RTibia )/NN
LAnklePower = POWER( LTibia, LFoot )/NN
RAnklePower = POWER( RTibia, RFoot )/NN

OUTPUT(LHipPower,RHipPower,LKneePower,RKneePower,LAnklePower,RAnklePowe
r)
```

```
EndIf


{***************************************}
{*** Angular Velocities **************}

ANGULARVELOCITY( Pelvis, RFemur, RHip, 0 )
ANGULARVELOCITY( Pelvis, LFemur, LHip, 1 )
ANGULARVELOCITY( RFemur, RTibia, RKnee, 0 )
ANGULARVELOCITY( LFemur, LTibia, LKnee, 1 )
ANGULARVELOCITY( RTibia, RFoot, RAnkle, 0 )
ANGULARVELOCITY( LTibia, LFoot, LAnkle, 1 )


OUTPUT( RHipAngVel, LHipAngVel, RKneeAngVel, LKneeAngVel, RAnkleAngVel,
LAnkleAngVel )
```

Lumbar Spine:

1) Marker identification File

```
!MKR#2
[Markers]
LeftPelvis
MidPelvis
RightPelvis
LeftThorax
MidThorax
RightThorax

LeftPelvis, MidPelvis, RightPelvis
LeftThorax, MidThorax, RightThorax

[Angles]
LumbarAngles

[Axis Vis]
ORIGINPelvis
AXISXPelvis
AXISYPelvis
AXISZPelvis

ORIGINPelvis,AXISXPelvis
ORIGINPelvis,AXISYPelvis
ORIGINPelvis,AXISZPelvis

ORIGINThorax
AXISXThorax
AXISYThorax
AXISZThorax

ORIGINThorax,AXISXThorax
ORIGINThorax,AXISYThorax
ORIGINThorax,AXISZThorax


ORIGIN%AverageThorax
AXISX%AverageThorax
AXISY%AverageThorax
AXISZ%AverageThorax

ORIGIN%AverageThorax,AXISX%AverageThorax
ORIGIN%AverageThorax,AXISY%AverageThorax
ORIGIN%AverageThorax,AXISZ%AverageThorax

ORIGINCorrectedThorax
AXISXCorrectedThorax
AXISYCorrectedThorax
AXISZCorrectedThorax
```

```
ORIGINCorrectedThorax,AXISXCorrectedThorax
ORIGINCorrectedThorax,AXISYCorrectedThorax
ORIGINCorrectedThorax,AXISZCorrectedThorax
```

2) Model Parameter file

```
{* LumbarSpineAngles.mp template subject measurements file for use with the Lumbar
Spine Angles model*}
{* 22/09/2004 Timothy Pitt, Vaquita Software - www.vaquita.co.uk *}


{* ================================ *}
{* Patient Specific Parameters ==== *}

{* None *}


{* ================================ *}
{* Parameters to control the model = *}


{* ==========================================
  These define the "calibration" period, normally at the begining of the trial,
  when the subject is standing straight. This allows the model to calculate the
  orientation of the Pelvis segment relative to the thorax
*}

StaticStart = 90
StaticEnd = 100

{* ==========================================
  MidMarkerDepth defines the distance the middle marker is behind the main
  plate that gets attached to the patient. This should be the same for both
  segments. And you should only need to set it once.
  It's quite important that the orientation of the pelvis segment
  is defined correctly, otherwise the Euler angles will be difficult to
  interpret.
  If this value is correct, the segment should have it's sagittal plane
  in the plane of he main plate.
*}

MidMarkerDepth = 25


{* ================================ *}
{* Synthesis section ============== *}

{* ================================
  The Create variable switches on some code which creates a synthetic
```

```
   pair of segment marker sets. This allows me (or you) to do a bit of
   testing.
   Setting it to zero will switch it off, so you can use the model
   on a normal trial.
 *}

 Create = 0

 if Create then

 $LeftPelvis = { 20, 100, 330 }
 $MidPelvis = { 0, 0, 300 }
 $RightPelvis = { 20, -100, 330 }

 $LeftThorax = { 20, 100, 560 }
 $MidThorax = { 0, 0, 500 }
 $RightThorax = { 20, -100, 500 }

 endif

 {* ================================== *}
```

3) Lumbar Spine Model

```
{* Lumbar Spine Angles model *}
{* Calculates the relative angles between a pair of segments *}
{* Use the LumbarSpineAngles.mkr and LumbarSpineAngles.mp files with this model*}
{* 22/09/2004 Timothy Pitt, Vaquita Software - www.vaquita.co.uk *}

Macro AXISVISUALISATION(Segment)
        ORIGIN#Segment=0(Segment)
        AXISX#Segment={100,0,0}*Segment
        AXISY#Segment={0,100,0}*Segment
        AXISZ#Segment={0,0,100}*Segment
        output(ORIGIN#Segment,AXISX#Segment,AXISY#Segment,AXISZ#Segment)
Endmacro

macro DefineSegment( Seg )
  Seg#Centre = ( Left#Seg + Right#Seg ) / 2
  Seg#Orient = NORM( Left#Seg, Mid#Seg, Right#Seg )
  Seg#Bottom = CHORD( MidMarkerDepth, Mid#Seg, Seg#Centre, Seg#Centre +
Seg#Orient )
  Seg = [ Seg#Bottom, Left#Seg - Right#Seg, Seg#Bottom - Seg#Centre, yxz ]
endmacro

{* ================================== *}
{* Synthesis section ============== *}

if Create then
```

```
LeftPelvis = $LeftPelvis
MidPelvis = $MidPelvis
RightPelvis = $RightPelvis
LeftThorax = $LeftThorax
MidThorax = $MidThorax
RightThorax = $RightThorax

{* rotate the thorax markers a bit *}
DefineSegment( Thorax )
Thorax = Thorax + {0,0,-100}
%L = LeftThorax / Thorax
%M = MidThorax / Thorax
%R = RightThorax / Thorax

Angle = (SAMPLE-150)/20
if SAMPLE > 150 THEN
  Thorax = ROT( Thorax, {0,1,0}, Angle )
endif
SideAngle = (SAMPLE-350)/20
if SAMPLE > 350 THEN
  Thorax = ROT( Thorax, {1,0,0}, SideAngle )
endif

LeftThorax = %L * Thorax
MidThorax = %M * Thorax
RightThorax = %R * Thorax


OUTPUT( LeftPelvis, MidPelvis, RightPelvis )
OUTPUT( LeftThorax, MidThorax, RightThorax )

endif

{* ================================ *}

{* Define the basic segments from the markers *}

DefineSegment( Pelvis )
DefineSegment( Thorax )

AXISVISUALISATION( Pelvis )
AXISVISUALISATION( Thorax )

{* During the static period in the trial
  Find the orientation of pelvis relative to the Thorax
  i.e. in the local coordinate system of the Thorax
*}

if SAMPLE >= StaticStart AND SAMPLE <= StaticEnd then
  %StaticThorax = ATTITUDE(Pelvis) / Thorax
endif

{* take averages of orientation components *}
```

```
%AverageThoraxX = AVERAGE( %StaticThorax(1) )
%AverageThoraxZ = AVERAGE( %StaticThorax(3) )

%AverageThorax = [ {0,500,0}, %AverageThoraxX, %AverageThoraxZ, xyz ]

AXISVISUALISATION( %AverageThorax )

{* For the rest of the trial
  The Corrected Thorax is found
  relative to the basic one
*}

CorrectedThorax = ATTITUDE( %AverageThorax ) * Thorax
AXISVISUALISATION( CorrectedThorax )


{* Now we just pull the angles between the Pelvis
  and the Corrected Thorax
*}

LumbarAngles = < Pelvis, CorrectedThorax, yxz >

OUTPUT( LumbarAngles )
```

Appendix D: Reliability of physiological measures

1) Reliability of Physiological Passive Movements: Spine

Lumbar Spine reliability of clinical goniometer readings

	Right Lateral Flexion				Left Lateral Flexion			
	Test 1	Test 2	Mean	Diff	Test 1	Test 2	Mean	Diff
	20.2	20.1	20.15	0.1	20.2	20.1	20.15	0.1
	29	29.1	29.05	-0.1	29.1	29.1	29.1	0
	25	24.9	24.95	0.1	25	25	25	0
	18.1	18.4	18.25	-0.3	18.2	18.4	18.3	-0.2
	17.9	18.1	18	-0.2	18	18.2	18.1	-0.2
	25.1	24.8	24.95	0.3	24.4	24.3	24.35	0.1
	25.4	25.5	25.45	-0.1	23.2	23.2	23.2	0
	28.9	29	28.95	-0.1	28.9	29	28.95	-0.1
	24.9	25	24.95	-0.1	24.9	24.9	24.9	0
	25.2	25	25.1	0.2	24.8	24.9	24.85	-0.1
Mean	23.97	23.99	23.98	-0.02	23.67	23.71	23.69	-0.04
SD	3.97	3.92	3.94	0.19	3.89	3.85	3.87	0.11
LSD				4.21				2.41
COV	16.56	16.33			16.44	16.26		

	Flexion				Extension			
	Test 1	Test 2	Mean	Diff	Test 1	Test 2	Mean	Diff
	60	62	61	-2	26.7	22	24.35	4.7
	54.3	58.7	56.5	-4.4	44.7	44.7	44.7	0
	49.7	49.7	49.7	0	18	18.7	18.35	-0.7
	54	56.3	55.15	-2.3	11	12	11.5	-1
	53.7	55.3	54.5	-1.6	20.7	17.7	19.2	3
	49.7	44.3	47	5.4	32	32.7	32.35	-0.7
	41.7	41.7	41.7	0	25.3	25.1	25.2	0.2
	46.7	45.3	46	1.4	42	41	41.5	1
	47	50.7	48.85	-3.7	33.7	29.3	31.5	4.4
	48	48.1	48.05	-0.1	47.9	48.2	48.05	-0.3
Mean	50.48	51.21	50.85	-0.73	30.20	29.14	29.67	1.06
SD	5.15	6.67	5.79	2.80	12.12	12.29	12.16	2.17
LSD				6.33				4.91
COV	10.20	13.03			40.14	42.18		

	RLF	LLF	Flex	Ext
LSD	4.21	2.41	6.33	4.91
Mean CoV	16.44	16.35	11.39	40.98
Mean diff	0.16	0.08	2.09	1.60
SD diff	0.08	0.08	1.90	1.76
PPMCC	0.999	1.000	0.919	0.984

2) Reliability of Physiological Passive Movements: Hip

Test retest reliability of hip movement: goniometer				
	Flexion 1	Flexion 2	Diff	Mean
	143	142	1	142.5
	140	141	-1	140.5
	150	150	0	150
	142	141	1	141.5
	149	150	1	149.5
	135	137	2	136
	145	148	3	146.5
	139	141	2	140
	141	145	4	143
	139	142	3	140.5
Mean	142.3	143.7	1.6	143
SD	4.64	4.37	1.51	4.43

Test retest reliability of hip movement: goniometer				
	Extension 1	Extension 2	Diff	Mean
	20	19	1	19.5
	17	18	1	17.5
	18	18	0	18
	19	20	-1	19.5
	20	21	-1	20.5
	21	20	1	20.5
	15	16	-1	15.5
	17	18	-1	17.5
	17	19	-2	18
	18	19	-1	18.5
Mean	18.2	18.8	-0.4	18.50
SD	1.81	1.40	1.07	1.55

Test retest reliability of hip movement: goniometer				
	Abduction 1	Abduction 2	Diff	Mean
	45	44	1	44.5
	44	42	2	43
	40	42	-2	41
	38	39	-1	38.5
	40	42	-2	41
	45	47	-2	46
	43	44	-1	43.5
	45	47	-2	46
	40	40	0	40
	39	38	1	38.5
Mean	41.9	42.5	-0.6	42.20
SD	2.77	3.06	1.51	2.82

Test retest reliability of hip movement: goniometer				
	Adduction 1	Adduction 2	Diff	Mean
	20	19	1	19.5
	27	26	1	26.5
	30	29	1	29.5
	25	27	-2	26
	29	28	1	28.5
	30	30	0	30
	27	27	0	27
	25	28	-3	26.5
	31	30	1	30.5
	29	30	-1	29.5
Mean	27.3	27.4	-0.1	27.35
SD	3.30	3.27	1.45	3.21

Test retest reliability of hip movement: goniometer				
	External Rotation 1	External Rotation 2	Diff	Mean
	70	69	1	69.5
	69	67	2	68
	65	66	-1	65.5
	60	63	-3	61.5
	63	64	-1	63.5
	68	67	1	67.5
	63	65	-2	64
	60	61	-1	60.5
	69	67	2	68
	62	62	0	62
Mean	64.9	65.1	-0.2	65
SD	3.84	2.56	1.69	3.15

Test retest reliability of hip movement: goniometer				
	Internal Rotation 1	Internal Rotation 2	Diff	Mean
	27	26	1	26.5
	30	31	-1	30.5
	31	32	-1	31.5
	28	29	-1	28.5
	29	30	-1	29.5
	30	26	4	28
	32	32	0	32
	28	27	1	27.5
	34	33	1	33.5
	36	37	-1	36.5
Mean	30.5	30.3	0.2	30.4
SD	2.84	3.47	1.62	3.06

Overview of physiological joint measurement for test retest

	Flexion	Extension	Abduction	Adduction	Rotation	
					Ext.	Int.
Mean Diff (°)	1.60	1.00	1.40	1.10	1.40	1.20
SD Diff	1.51	0.47	0.70	0.88	0.84	1.03
LSD (°)	3.87	2.43	3.41	3.28	3.81	3.66
PPMCC (r)	0.93	0.85	0.87	0.90	0.94	0.89

Key:
SD – Standard deviation, Mean Diff - Mean difference between test 1 & 2
SD Diff - SD difference between test 1 & 2, LSD - Least Significant Difference
PPMCC - Pearson Product Moment Correlation Co-efficient (r)

3) Intra-rater reliability of true leg length measurements

Reliability of True Leg length measurement

	Test 1	Test 2	Differences	Mean
	89.5	89	0.5	89.25
	87.5	87	0.5	87.25
	94.5	94.5	0	94.5
	83	83	0	83
	91	90.5	0.5	90.75
	80	80	0	80
Mean	87.58	87.33	0.25	87.46
SD	5.32	5.23	0.27	5.28
PPMCC (r)		0.999		
LSD	t = 2.571		0.69	

Appendix E: Total Hip Replacement Group Invitation letter

Dear ....

Mr.McAuliffe, your consultant orthopaedic surgeon has given me permission to contact you. I understand that you had a total hip replacement approximately 1 year ago and I am writing to ask you if you are willing to take part in some important research?

What is the research about?

We are looking at the way people over 65 years of age move when they do 3 particular activities, these are: walking, standing up from sitting and leaning forward in a chair. We want to compare the way people move following a hip replacement with those who have not had one.

What you will be asked to do?

If you agree to participate you will be asked to attend the Motion Analysis Laboratory at The University of East London, Romford Road, Stratford, on one occasion, which normally lasts approximately 2.5 hours. (Full address and travel details will be given on acceptance of testing). When you come to the laboratory you will be asked to give some personal details (age, address, contact number, etc.) and then you will be weighed and your height taken. Following this you will be asked to put on a pair of shorts and a sleeveless top (you may bring your own clothes for comfort, if you wish but we can provide these if necessary) and to take off your shoes and socks. Sticky backed markers will be attached to you and your movements will be recorded by cameras, which produce a stick figure of your movement. A number of measurements will be taken whilst you lean forward in sitting, move from sitting into standing and walk. You will be asked to do these movements at least five times, but if you are troubled by any of these activities then the test can be stopped. If all the measurements have been recorded then you will not need to attend again.

If you wish to stop the test at any time, you may do so with no disadvantage to yourself. You will be given £10 towards the cost of transportation for your visit to the University.

What to do if you wish to take part?

If you could spare the time and would like to participate then please contact **Fiona Coutts** on **020 8223 4025**. If you would like any questions answered before committing yourself we will gladly help, please contact the number above. If I do not hear from you within 2 weeks I will follow-up this letter by telephone.

Thank you for your time in reading this letter and I hope you will find this project both worthwhile and interesting to help understand the recovery of movement for those with Total Hip Replacement.

Yours sincerely,

Fiona Coutts M.Sc. MCSP
Principal Lecturer in Physiotherapy
Tel No. 020 8223 4025 (If answer phone is on, please leave name and contact number)
Email: F.J.Coutts@uel.ac.uk

Appendix F: Confirmation Letter

Dear

Thank you for agreeing to take part in the study on "**Biomechanical analysis of the return of functional activity after Total Hip Replacement, comparison with age matched normals.**"

You have kindly suggested dates that are suitable for you to come to be measured at the Human Movement Laboratory at the University of East London. Taking into account availability of others the best date would appear to be:

Date:

Time:

Place: Human Motion Performance Laboratory (UH 207)
University of East London, Romford Road, Stratford.

Contact telephone number: 020 8223 4025

If this appointment is not convenient to you please contact me on the telephone number above **after January 5th** and I will gladly change it. The map attached indicates how to get to the University of East London, Stratford Campus. The nearest tube and train station is STRATFORD, on the central line. If arriving on foot, please go to the main entrance of University House on Romford Road where there is a reception desk. If arriving by car, please let me know before your appointment and I will meet you to let you in to the car park at the side entrance to the building off Water Lane (marked on the map).

If you have any questions at all please contact me on the number above. May I take this opportunity to remind you to bring a loose fitting sleeveless top and shorts, if you do not have a either of these I can supply these at the laboratory.

Many thanks for your help and I look forward to seeing you at the University.
Yours sincerely,

Fiona Coutts M.Sc. MCSP
Principal Lecturer in Physiotherapy

Appendix G: Information Sheet

A) THR group

Written Explanation for Potential Subjects

This study is being undertaken in the Human Motion and Performance Laboratory at the University of East London, Romford Road, Stratford, London. Tel. Number 020 8223-4025. The principle tester is Miss Fiona Coutts, a qualified physiotherapist who will be assisted by physiotherapy students. Mr. T. McAuliffe, Consultant Orthopaedic Surgeon is the lead member of the research team but will not be taking part in the measurement at the University. All the data will be made available to Mr. McAuliffe, who has given full consent to the collection of this data as part of your follow up care.

You have been asked to volunteer to participate in this study to assist with physiotherapy research into the amount and sequence of movement at the hip and spine. The results of this research will help physiotherapists to give effective treatment when loss of movement or pain at the hip or the spine after Total Hip Replacement is an issue.

What happens in the laboratory?

When you come to the University you will be asked to give some personal details (age, address, contact number, etc.) and then you will be weighed and your height taken. Following this you will be asked to put on a pair of shorts and a top and to take off your shoes and socks. Whilst in standing an assistant will identify muscles on your leg, mark several bony landmarks and take measurements of your leg. You will then be asked to lie on a plinth and your leg length and hip movement will be measured. In standing measurements of your spinal movement will be taken then small round markers will be placed on the bony points identified above. This will not affect your movement in any way. (see photograph attached).

Adhesive tape may be used to keep clothing in place, therefore **it is important that you tell us if you are allergic to adhesive tape.**

With all the measurement tools in place you will be able to move normally and you should not feel any discomfort. You will be asked to do the following:

- Stand still for 2 seconds,
- Bend forward as far as possible with your arm out in front,
- Sit on a stool for 2 seconds,
- In sitting bend forward as far as possible,
- Move from sitting on the stool into standing,
- Move from standing to sitting,
- Walk over a 10m distance,
- Stand still for 2 seconds.

You will be asked to do these movements at least **five times**, but if you are troubled by any of these activities then the test can be stopped. If you wish to stop the test at any time, you may do so with no disadvantage to yourself.

You will be given £10 towards the cost of transportation for your visit to the University. PTO

B) Non-THR group

Written Explanation for Potential Subjects

This study is being undertaken in the Human Motion and Performance Laboratory at the University of East London, Romford Road, Stratford, London. Tel. Number 020 8223-4025. The principle tester is Miss Fiona Coutts, a qualified physiotherapist who will be assisted by physiotherapy students.

You have been asked to volunteer to participate in this study to assist with physiotherapy research into the amount and sequence of movement at the hip and spine. The results of this research will help physiotherapists to give effective treatment when loss of movement or pain at the hip or the spine after Total Hip Replacement is an issue.

What happens in the laboratory?

When you come to the University you will be asked to give some personal details (age, address, contact number, etc.) and then you will be weighed and your height taken. Following this you will be asked to put on a pair of shorts and a top and to take off your shoes and socks. Whilst in standing an assistant will identify muscles on your leg, mark several bony landmarks and take measurements of your leg. You will then be asked to lie on a plinth and your leg length and hip movement will be measured. In standing measurements of your spinal movement will be taken then small round markers will be placed on the bony points identified above. This will not affect your movement in any way. (see photograph attached).

Adhesive tape may be used to keep clothing in place, therefore **it is important that you tell us if you are allergic to adhesive tape.**

With all the measurement tools in place you will be able to move normally and you should not feel any discomfort. You will be asked to do the following:

- Stand still for 2 seconds,
- Bend forward as far as possible with your arm out in front,
- Sit on a stool for 2 seconds,
- In sitting bend forward as far as possible,
- Move from sitting on the stool into standing,
- Move from standing to sitting,
- Walk over a 10m distance,
- Stand still for 2 seconds.

You will be asked to do these movements at least **five times**, but if you are troubled by any of these activities then the test can be stopped. If you wish to stop the test at any time, you may do so with no disadvantage to yourself.

You will be given £10 towards the cost of transportation for your visit to the University.

PTO

University of East London, Human Motion Performance Laboratory

"Biomechanical analysis of the return of functional activity after Total Hip Replacement, comparison with age matched normals."

Strap and wires will not be present for this study

Lightweight reflective markers, attached by double sided sticky tape

Pictures of a participant being measured in the Human Motion Performance Laboratory at the University of East London. **Participants for the study into Total Hip Replacement will wear loose fitting shorts and sleeveless tops** and will NOT have a strap over the shoulder or wires attached as per this picture. Markers such as these round white spheres will be placed on the leg and the back.

Fiona Coutts
Principal Lecturer in Physiotherapy

Appendix H: Consultant letter of consent to use patients

Forest
Healthcare

21 July 1999

Fiona Coutts
Department of Health Sciences
University of East London
Romford Rd
London
E15 4LZ

Whipps Cross Hospital
Whipps Cross Road
Leytonstone
London E11 1NR
Telephone 0181-539 5522
Fax 0181-558 8115

Dear Fiona

Thank you for your letter regarding the proposed study of the relationship between hip and lumbar spine motion in total joint replacement.

I am quite happy for my patients to take part in this study. You will appreciate of course that many of them are quite elderly and may not be willing to take part in the study, or may find it difficult to do so. It may be better therefore targeting the slightly younger group.

I would like to see the full method and draft letter of invitation. Since this is not a trial but an assessment I can see no reason why we should need to involve the ethics committee.

Yours sincerely

T.B. McAuliffe MA FRCS
Consultant Orthopaedic Surgeon

600392

Chairman
Clive Myers

Chief Executive
Bryan Harrison
Forest Health NHS Trust

Appendix I: Informed Consent

WRITTEN CONSENT FORM:

Title of research proposal: **Biomechanical analysis of the return of functional activity after Total Hip Replacement, comparison with age matched normals.**

Study Number:
Name of Patient: ______________________________

Address: ______________________________
____

I have read the attached information on the research in which I have been asked to participate and have been given a copy to keep. I have had the opportunity to discuss the details and ask questions about this information.

The Investigator has explained the nature and purpose of the research and I believe that I understand what is being proposed. I have been made aware that this trial is part of a research project designed to promote medical knowledge, and that it has been approved by the University of East London Research Ethics Committee, and that I can withdraw from the research at any time.

I have been informed that the proposed study involves monitoring and should present no possible risk to myself.

I understand that my personal involvement and my particular data from this trial will remain strictly confidential. Only researchers involved in the trial will have access.

I also understand that my General Practitioner will be informed that I have taken part in this study, if I so wish.

I hereby fully and freely consent to participate in the study, which has been fully explained to me.

PATIENT'S/VOLUNTEER'S NAME:(BLOCK CAPITALS) ....

PATIENT'S/VOLUNTEER'S NAME: SIGNATURE ....

PATIENT'S/VOLUNTEER'S WITNESS' NAME: ....

WITNESS' SIGNATURE: ....

DATE:...

The following should be signed by the Investigator responsible for obtaining consent.

As the Clinician/Investigator responsible for this research or a designated deputy, I confirm that I have explained to the patient/volunteer named above the nature and purpose of the research to be undertaken.

INVESTIGATOR'S NAME: ....

INVESTIGATOR'S SIGNATURE: ....

DATE: .... (Consent.doc)

Subjects are warned not to take part in more than one study at any time.

Appendix J: General Questions to Participants

I. PERSONAL INFORMATION

Name ____

Address: ____

Phone number: ______________________________________

Date of birth (day/month/year) ____/____/____ **Sex:** *M / F*

Height (to nearest half cm): _____,____*cm*

Weight (to nearest half kg): _____,____ *kg*

Dominant side: *L / R*

Operated side: *L / R/ NA*

Leg Length(cm): (R) (L)

Present status of operated leg:
Present status of non-operated leg:
Past History of operated leg:
Past History of non-operated leg:

General Questions: (Circle for yes) Diabetes, Epilepsy, Major surgeries, Heart, Rheumatoid arthritis, Cancer, History of vertigo, Middle ear problems, Leg or Back pain.

Recreational activities:

Occupation:

Date(s) of Hip replacement(s):

Date of surgery (day/month/year) ____/____/____(1st Hip)

Date of surgery (day/month/year) ____/____/____(2nd Hip)

Appendix K: Anthropometric Data Form

Subject Anthropometric Data

Subject Number

Patient Name ______________________________ Height (cm)____________

Weight (kg) ___________ Age____________

All measurements in centimetres	Date		Comments
	R leg	L leg	
Length of foot (Tip of heal to first metatarsal joint)			
Distance from lateral malleolus to lateral fem condyle (LFC)			
- 56.7% of this distance from (LFC)			
Distance from (LFC) to middle of greater trochanter (GT)			
- 58.7% of this distance from (GT)			
Distance from GT to ASIS			
Distance from GT to PSIS			
Distance between the ASIS to ASIS			
Distance from the ASIS to PSIS (R)			
Distance from the ASIS to PSIS (L)			
Circumference of upper thigh			
Circumference of mid thigh			
Circumference of knee at middle of knee			
Circumference of leg at malleolus level			
Circumference at middle of foot (top of dorsum)			
Circumference of foot around fifth metatarsal			
Distance from LFC - ant shank			
Distance from LM - ant shank			
Distance from LFC - ant thigh			
Distance from LGT- ant thigh			

Comments during Tests:

Appendix L: Analysis of Normal Distribution for all Physiological Data

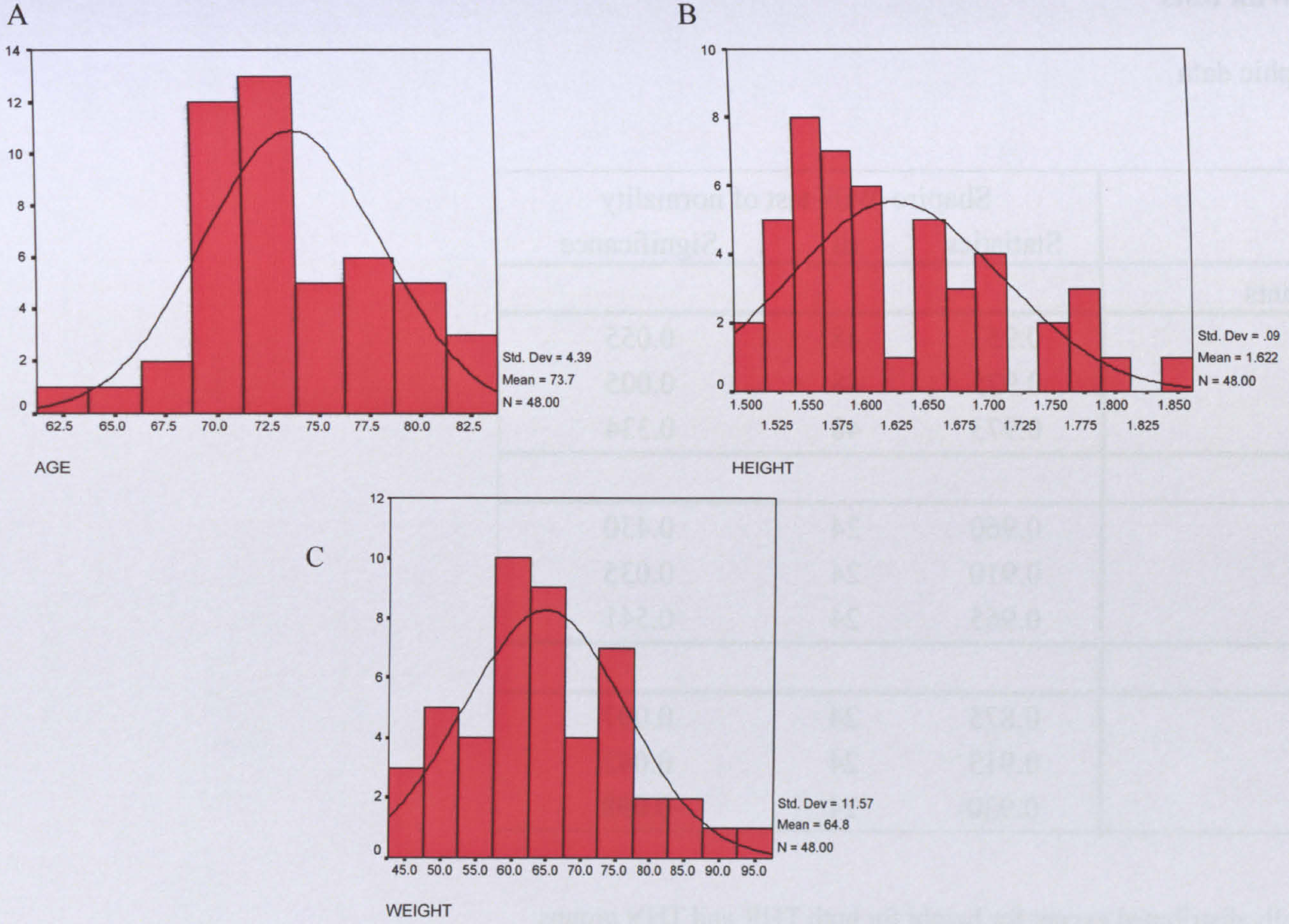
1) Shaprio-Wilk tests

A) Demographic data

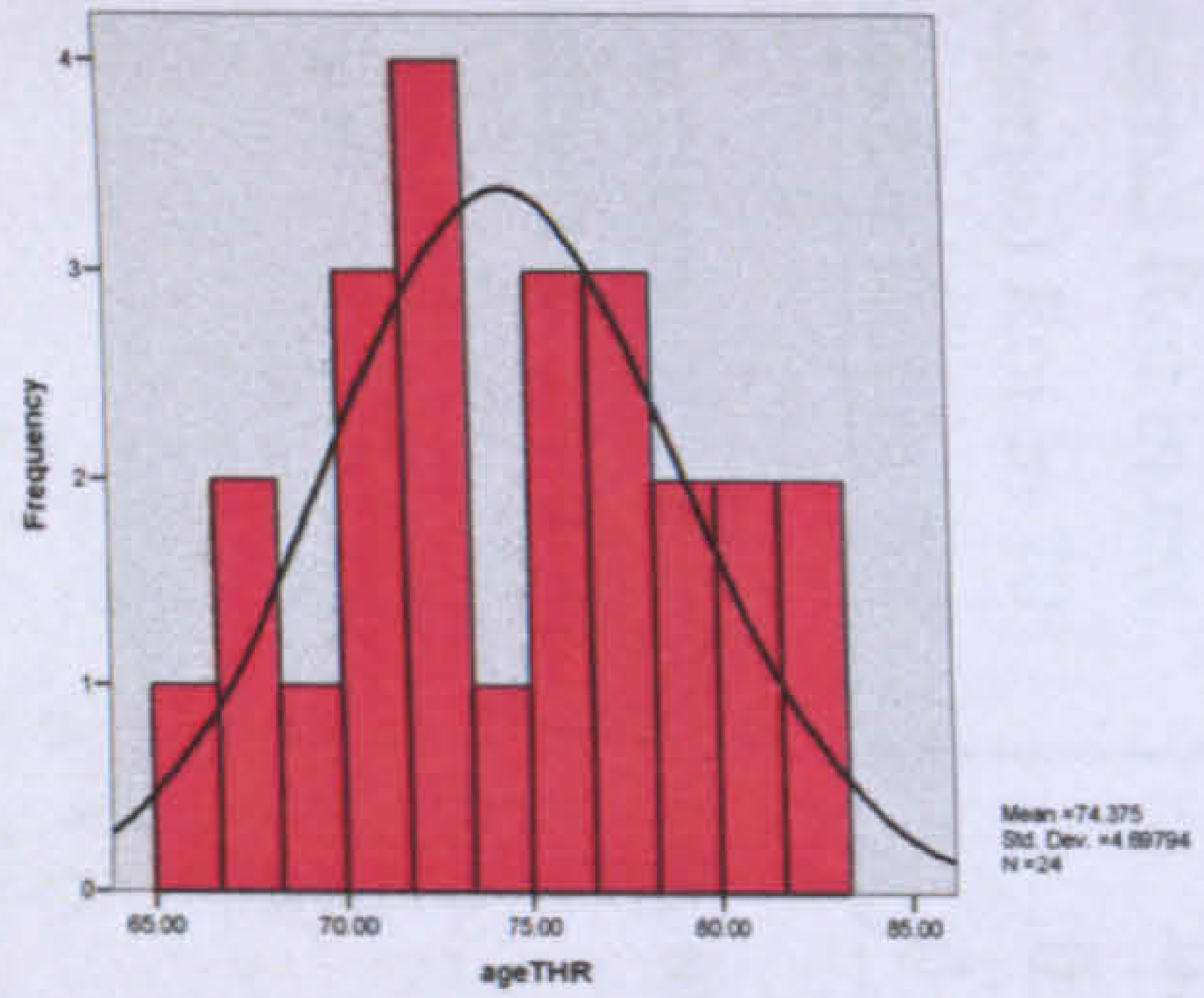
	Shapiro-Wilk test of normality		
	Statistics	df	Significance
All participants			
Age	0.953	48	0.055
Height	0.925	48	0.005
Weight	0.973	48	0.334
THR			
Age	0.960	24	0.430
Height	0.910	24	0.035
Weight	0.965	24	0.541
THN			
Age	0.875	24	0.007
Height	0.913	24	0.042
Weight	0.930	24	0.098

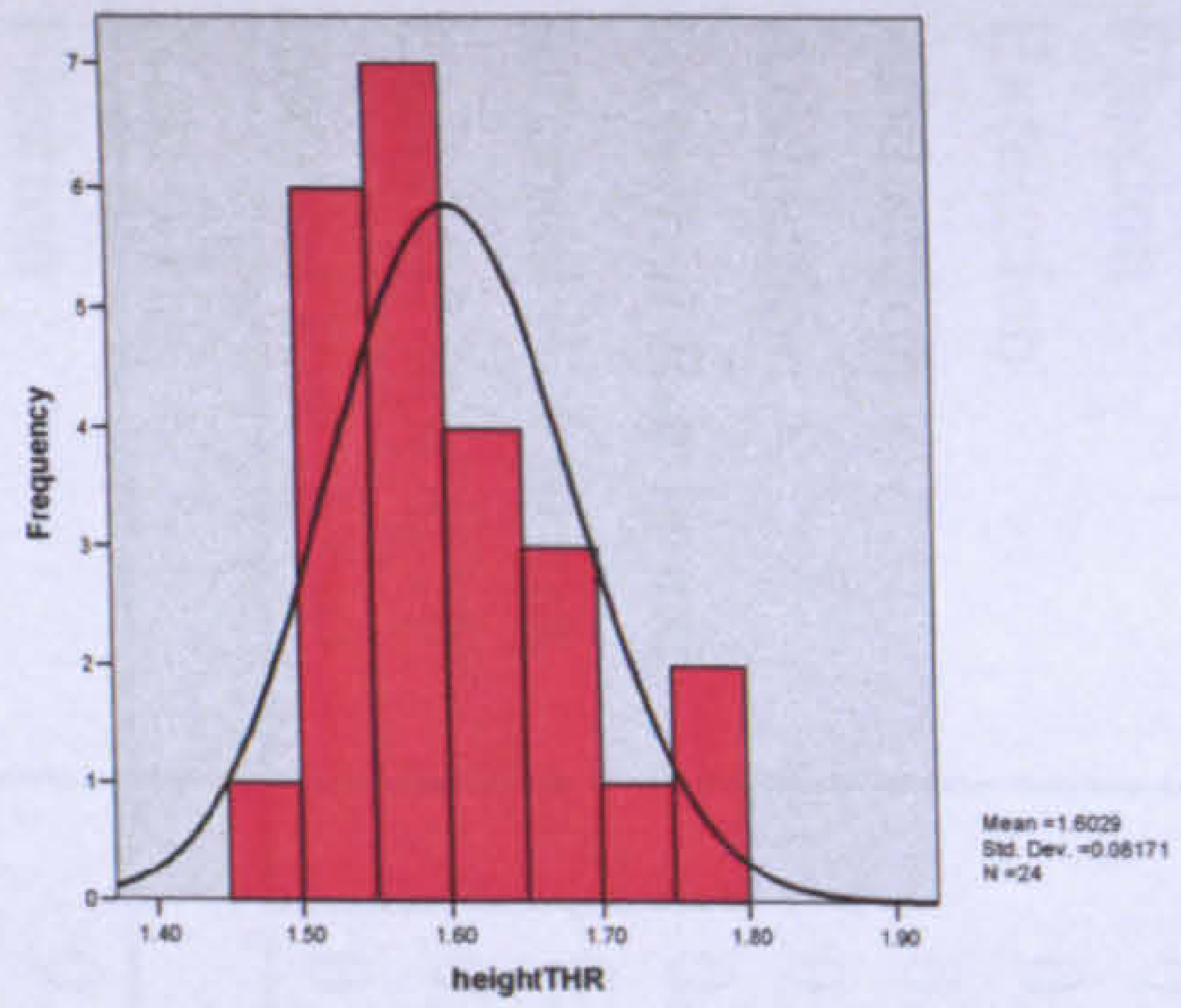
All data normally distributed except for height for both THR and THN groups

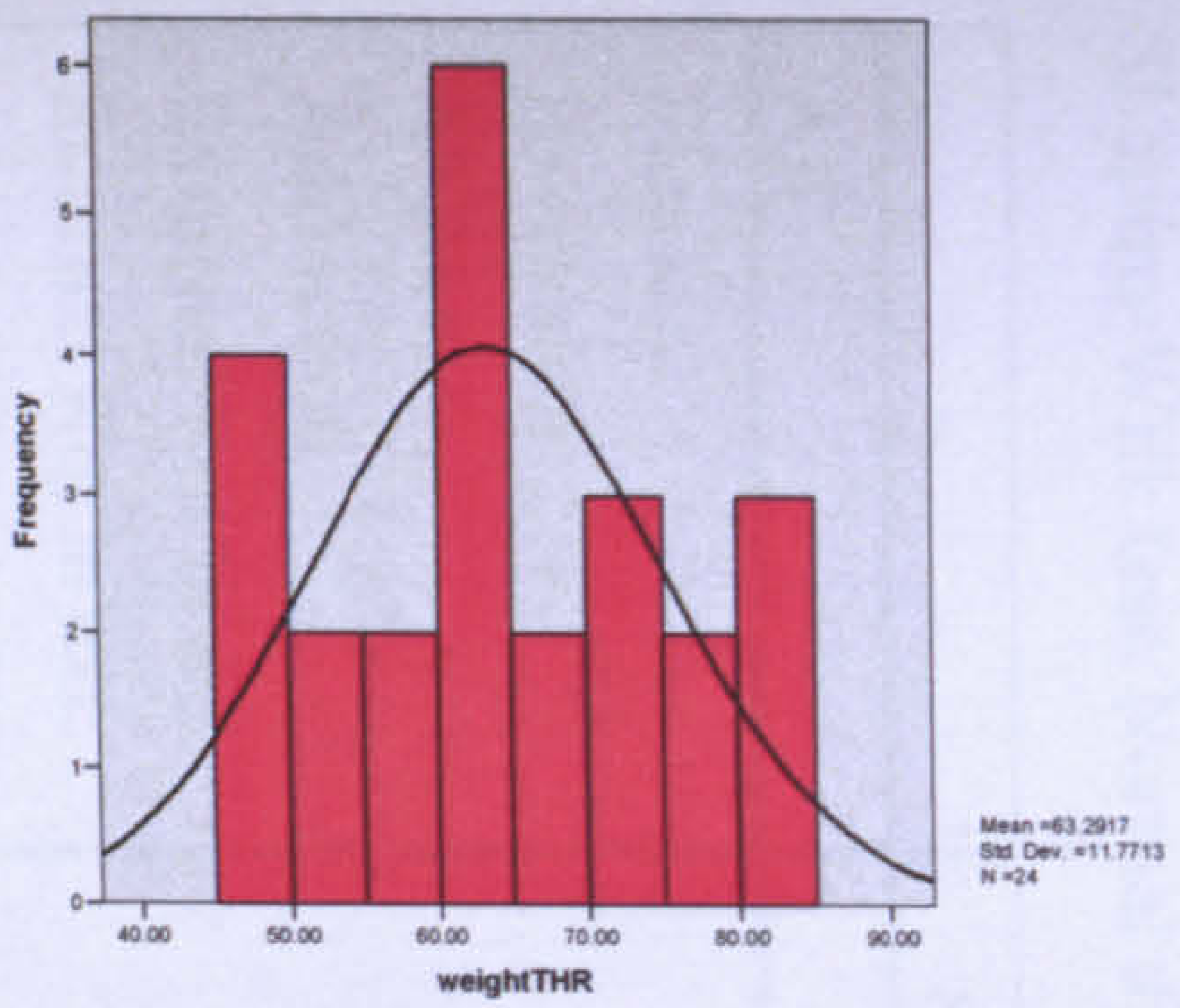
Demographic data Normal Distribution graphs (A, B, C)



Demographic data Normal Distribution graphs

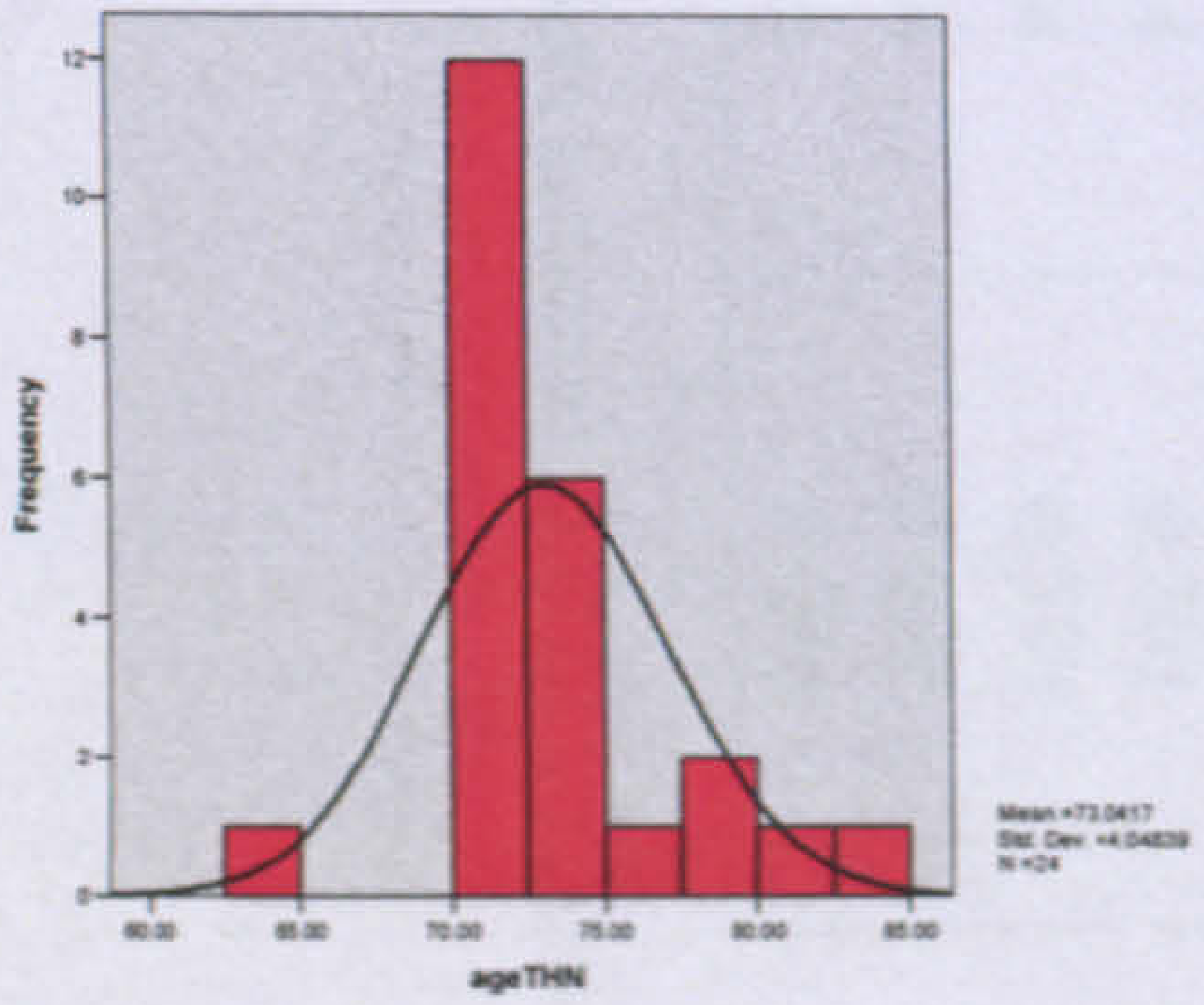


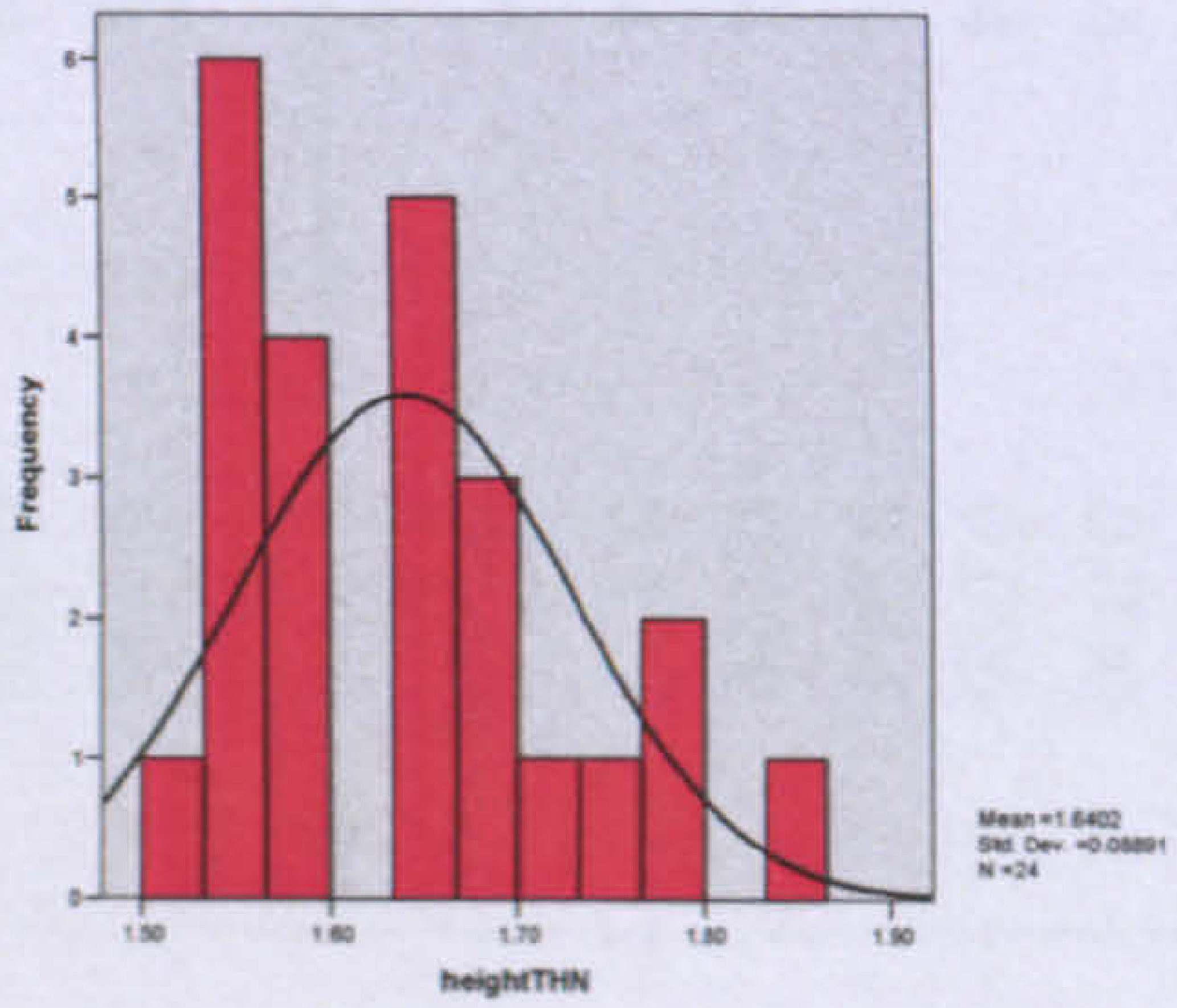


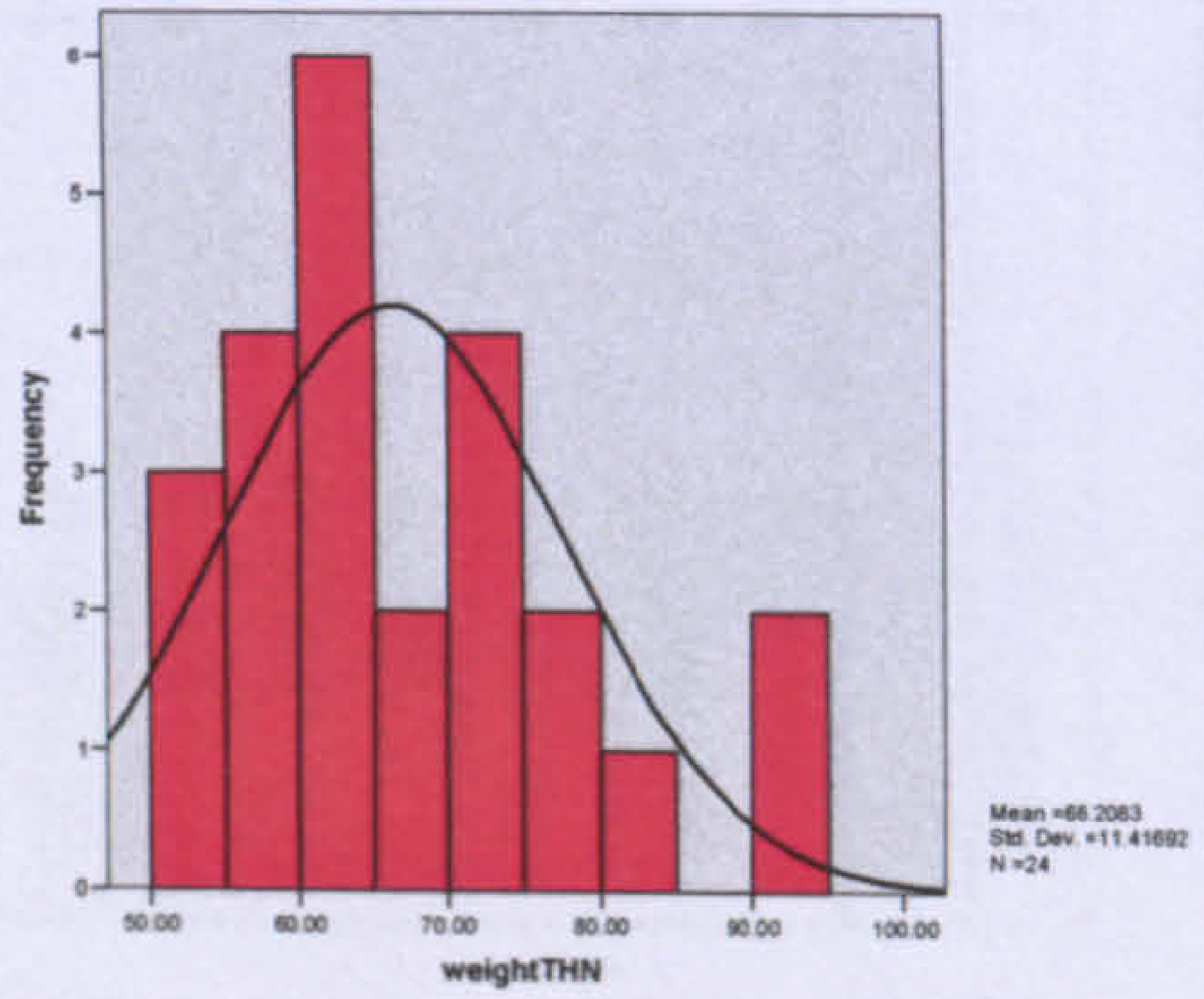


A THR- age
B THR - height
C THR - weight

D THN - age
E THN - height
F THN - weight





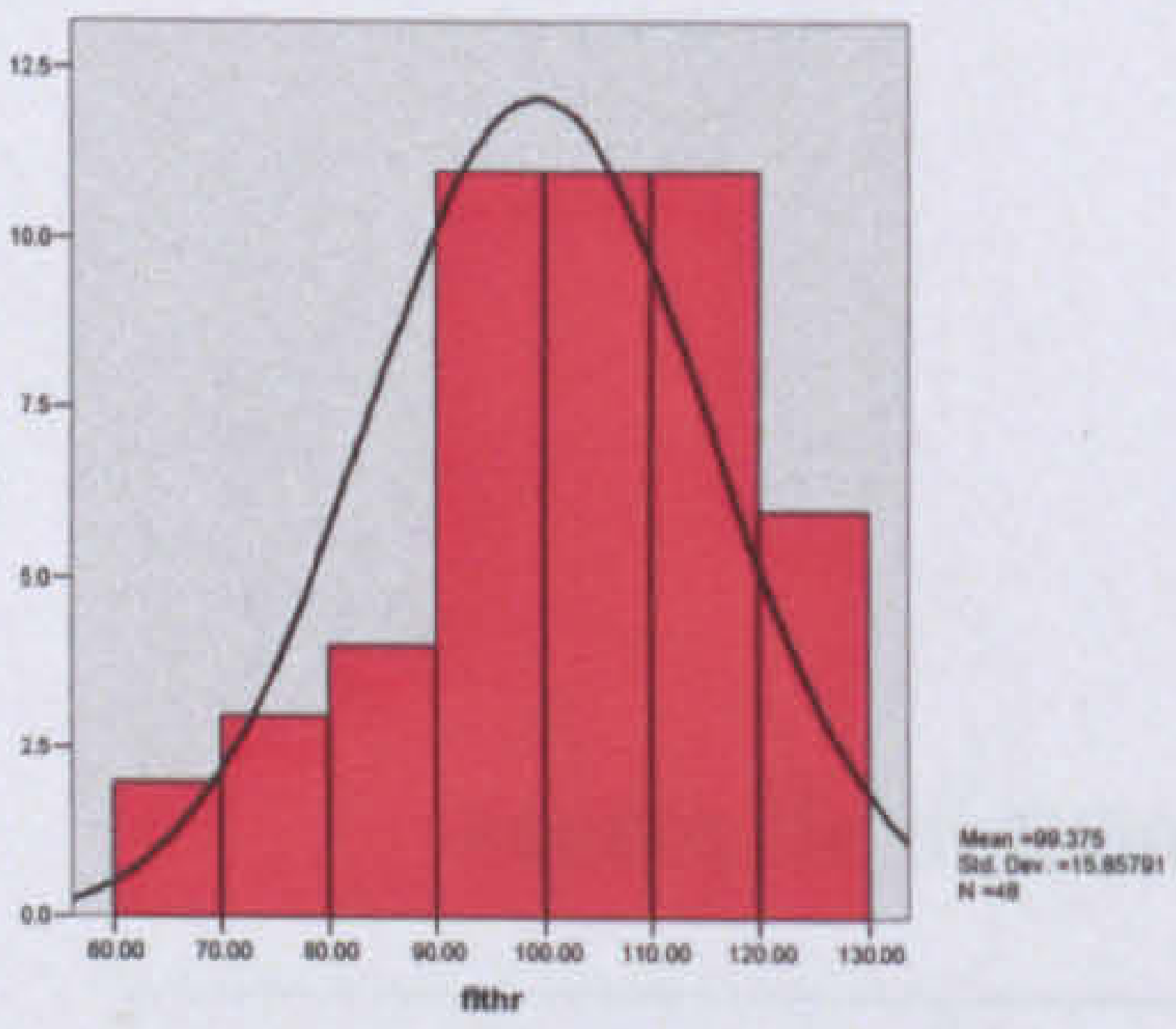


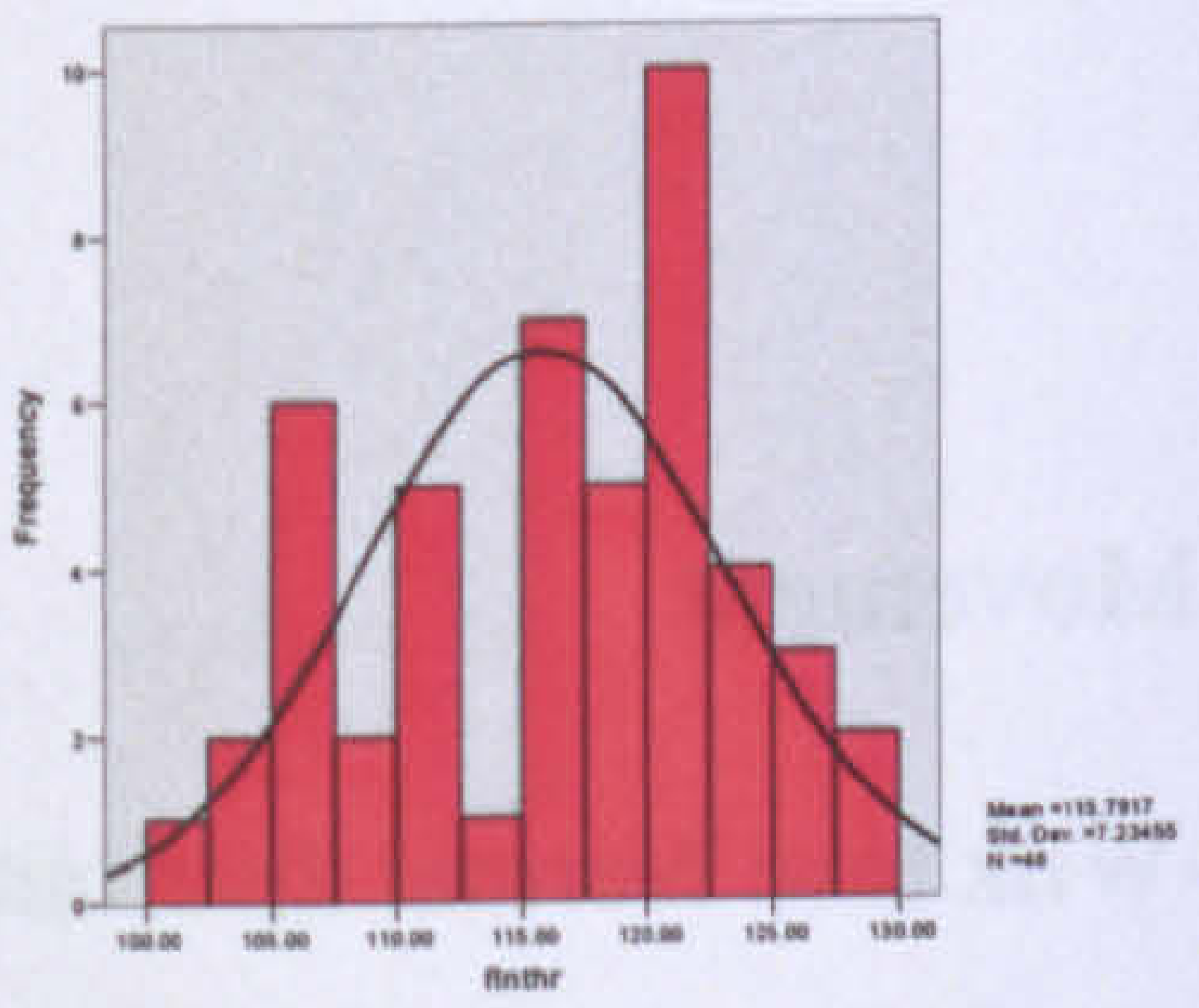
B) Hip Movement

Shapiro-Wilk test: Normal distribution: Hip movement in all planes

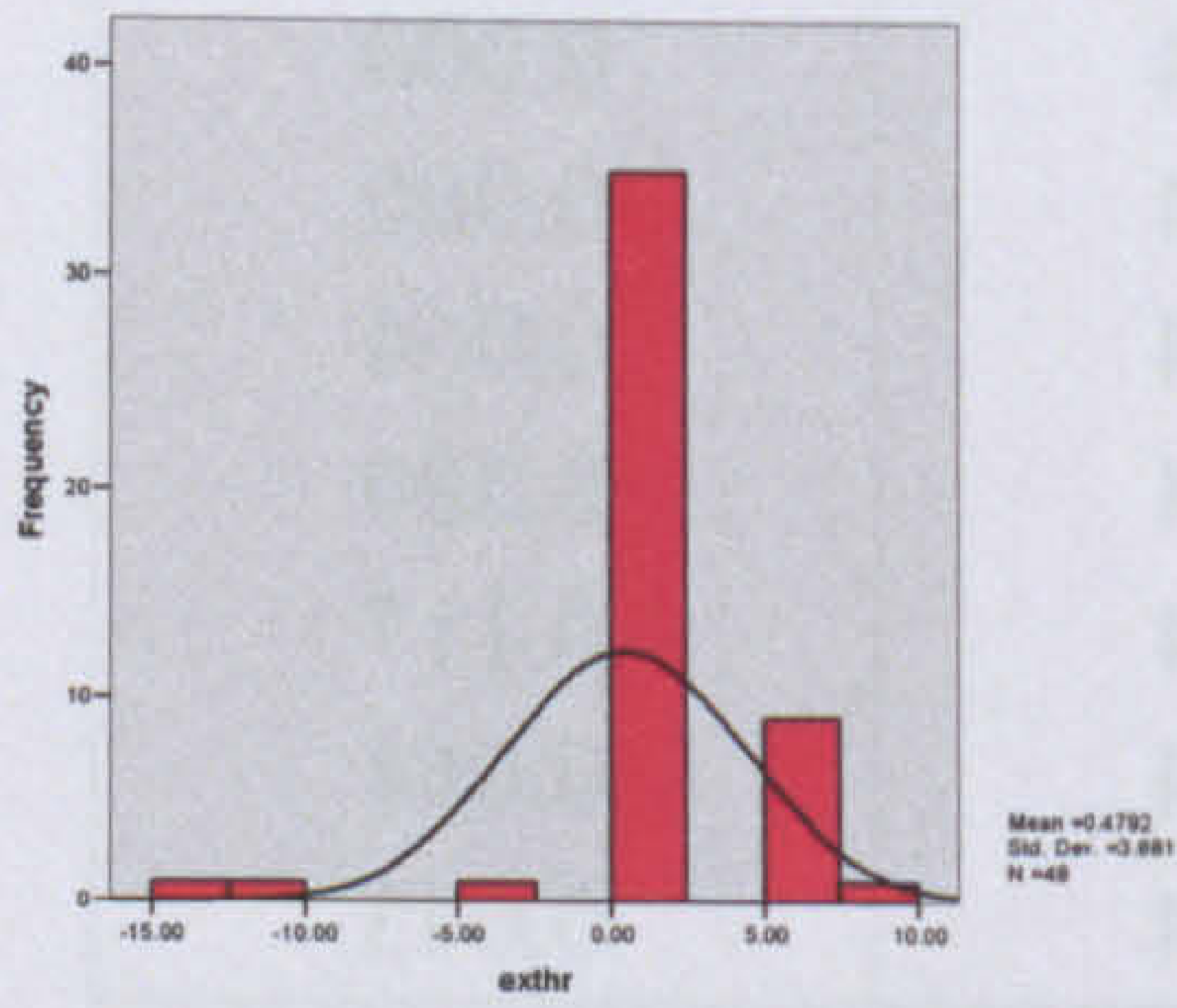
	Statistic	df	Significance
All			
Flexion	0.951	24	0.291
Extension	0.743	24	0.000
Abduction	0.872	24	0.006
Adduction	0.922	24	0.064
External Rot in ext.	0.951	24	0.280
Internal Rot in ext.	0.933	24	0.117
External Rot in 70°	0.922	24	0.064
Internal Rot in 70°	0.914	24	0.043
THR			
Flexion	0.951	24	0.291
Extension	0.743	24	0.000
Abduction	0.872	24	0.006
Adduction	0.922	24	0.064
External Rot in ext.	0.951	24	0.280
Internal Rot in ext.	0.933	24	0.117
External Rot in 70°	0.922	24	0.064
Internal Rot in 70°	0.914	24	0.043
Non-THR			
Flexion	0.971	24	0.695
Extension	0.882	24	0.009
Abduction	0.851	24	0.002
Adduction	0.942	24	0.177
External Rot in ext.	0.944	24	0.201
Internal Rot in ext.	0.967	24	0.589
External Rot in 70°	0.977	24	0.836
Internal Rot in 70°	0.928	24	0.090

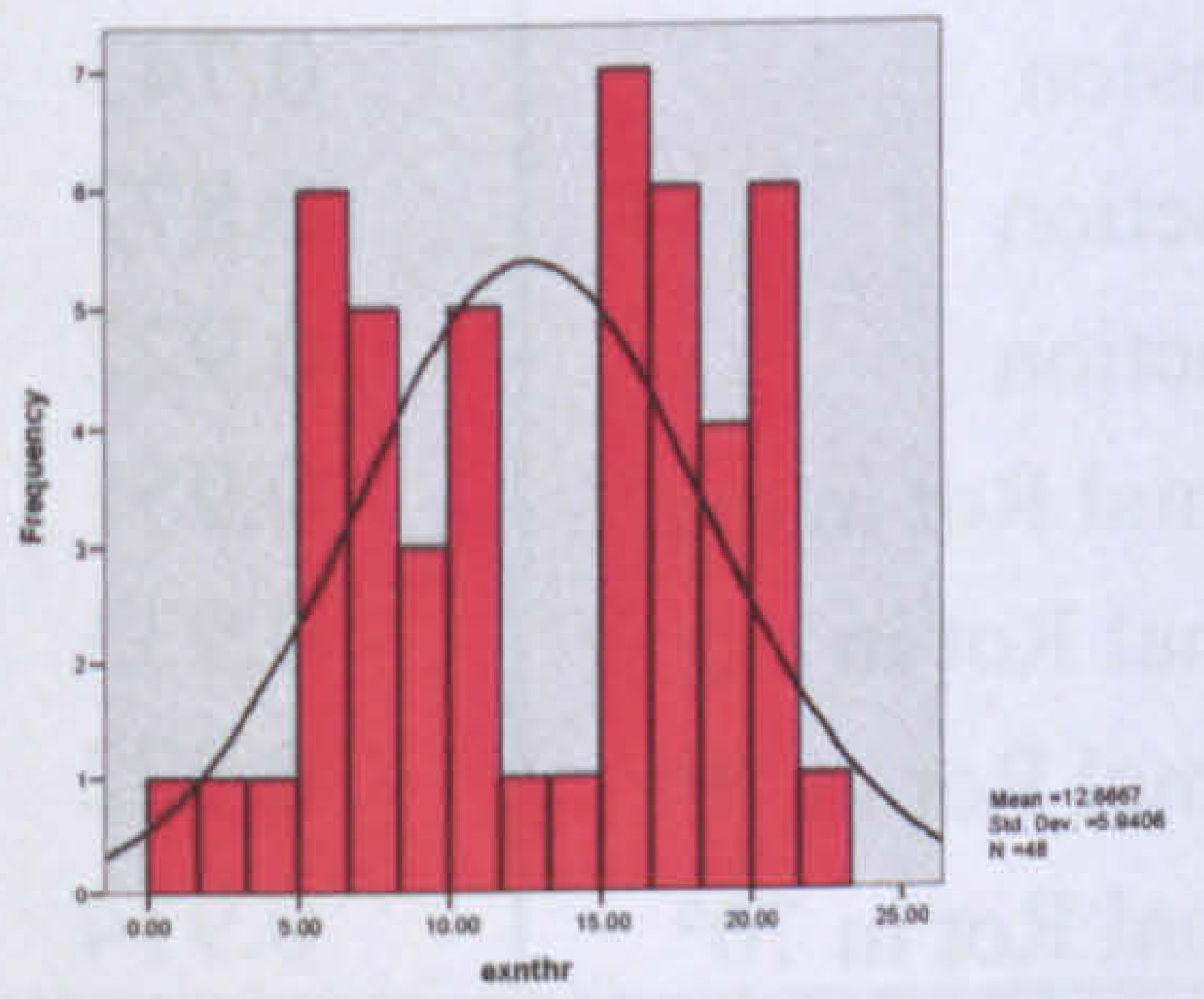
Hip extension, Abduction, and internal rotation in flexion (THR) not normally distributed



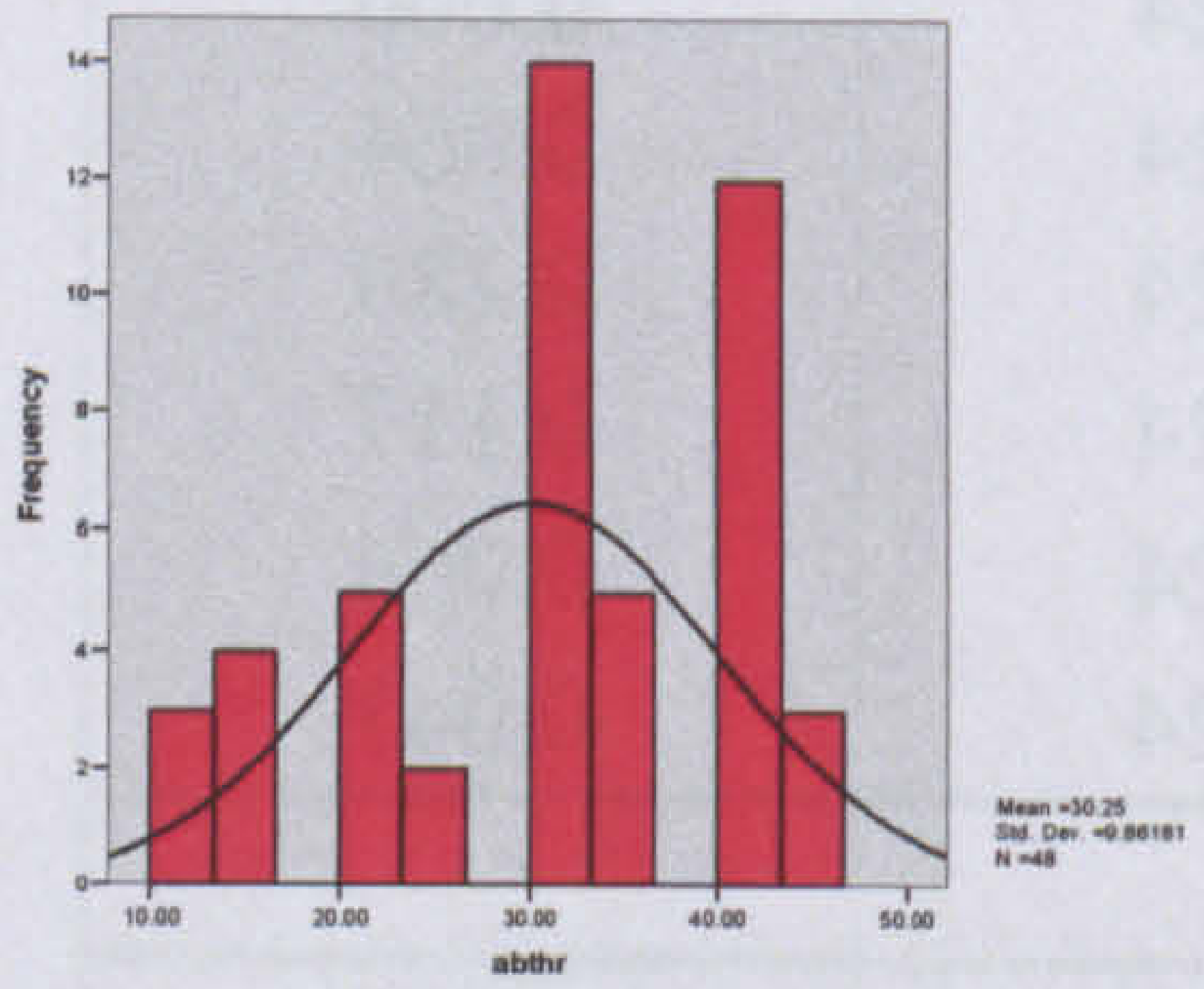


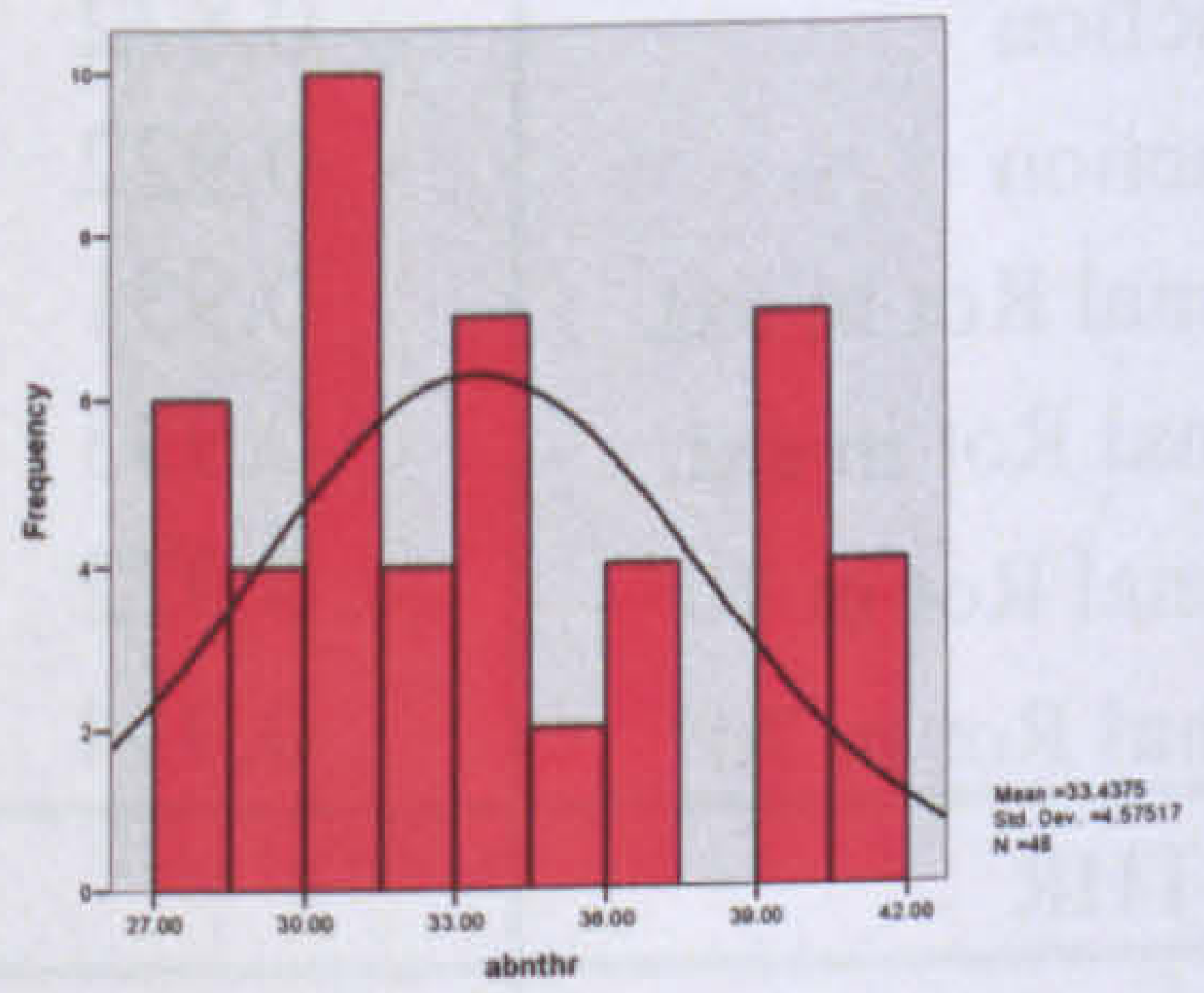
Flexion



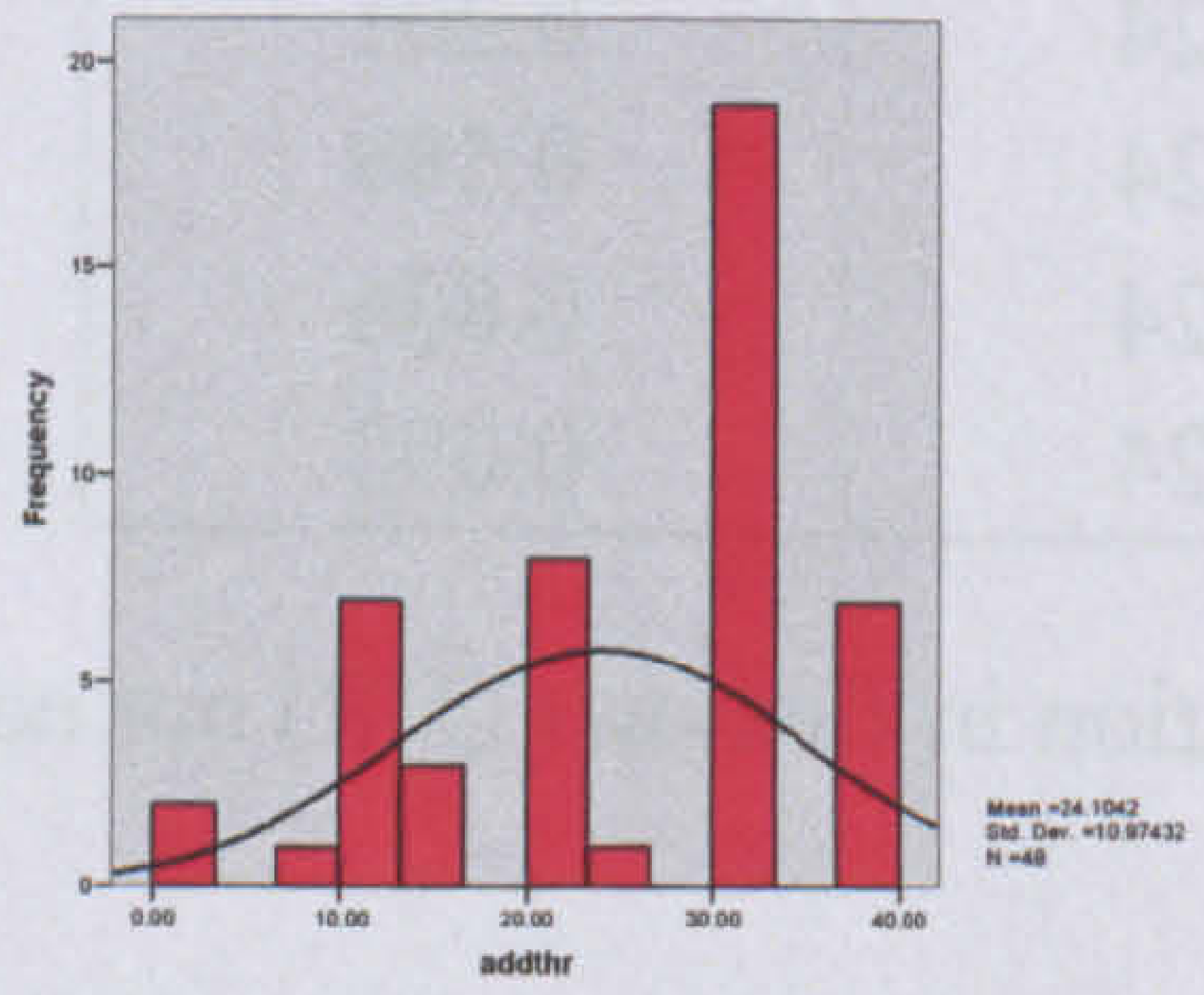


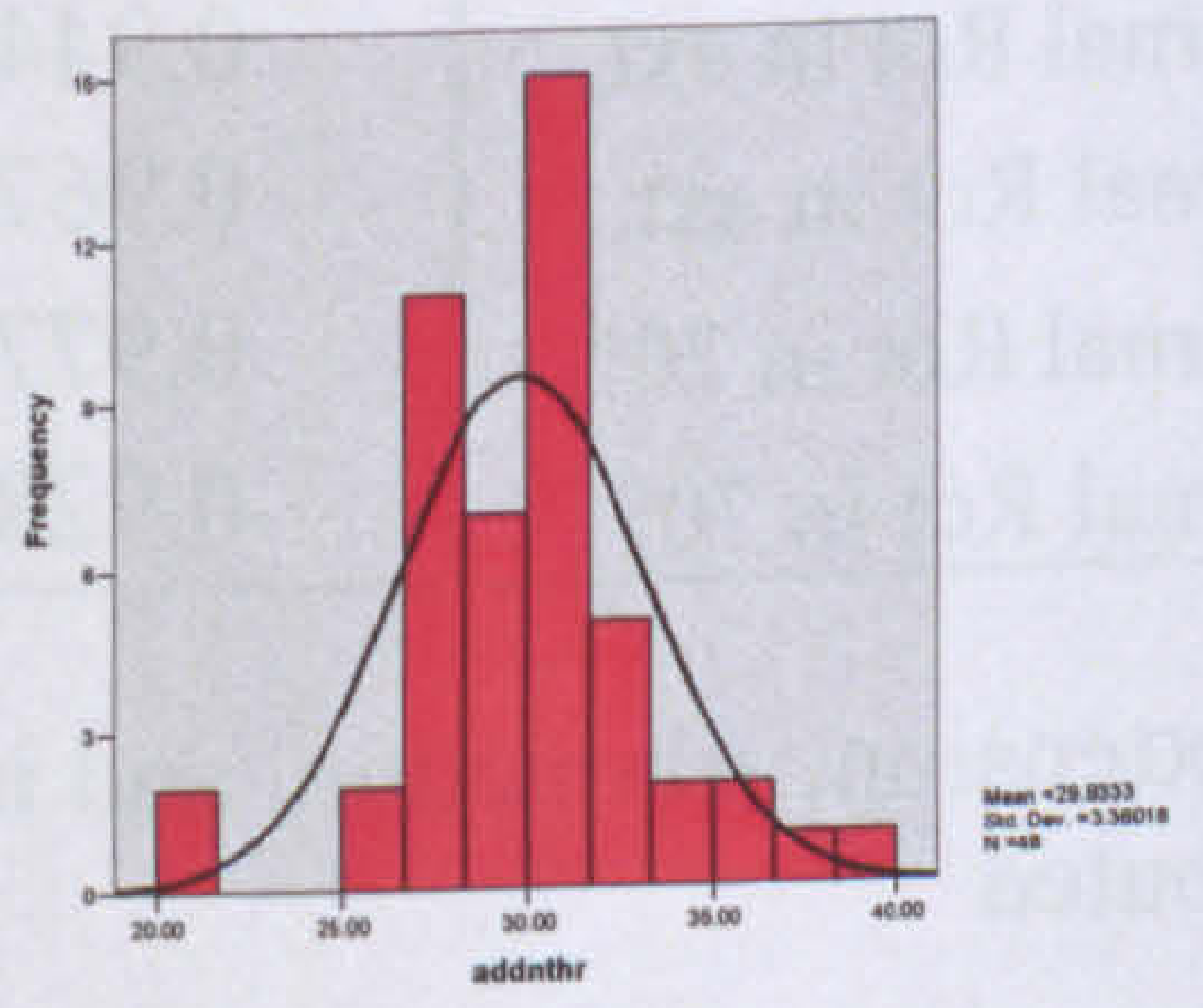
Extension





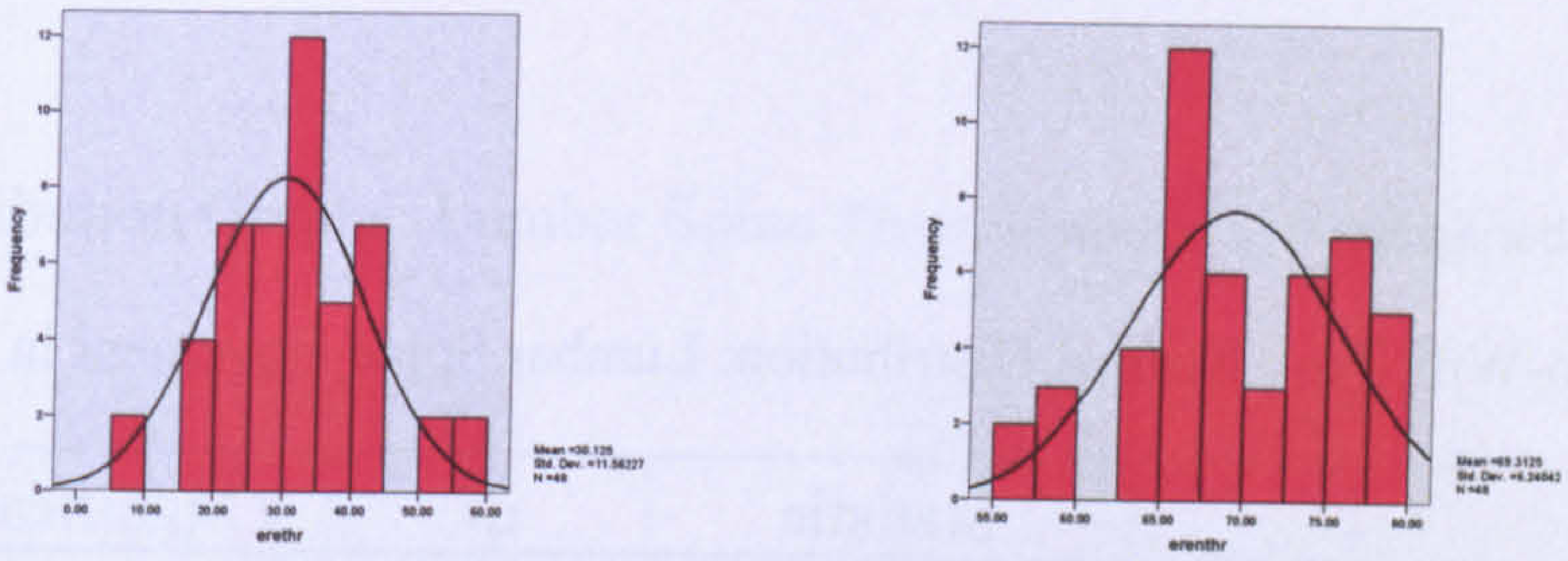
Abduction



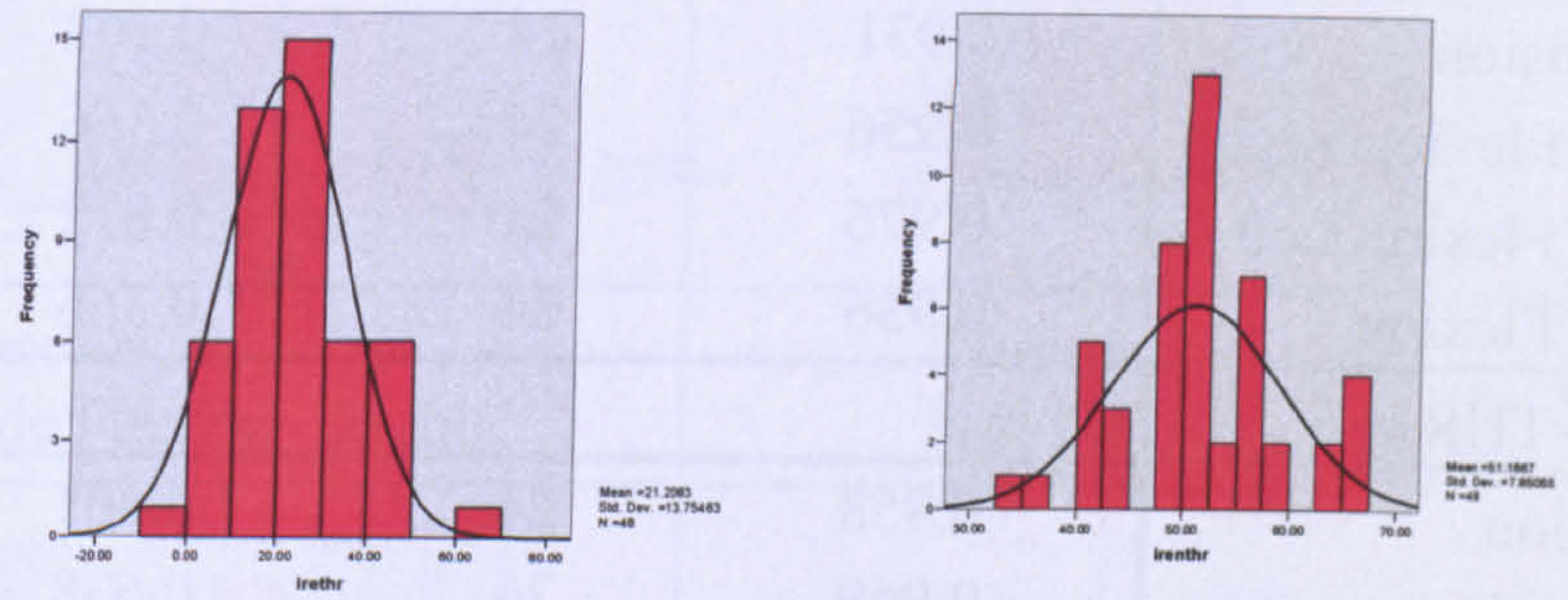


Adduction

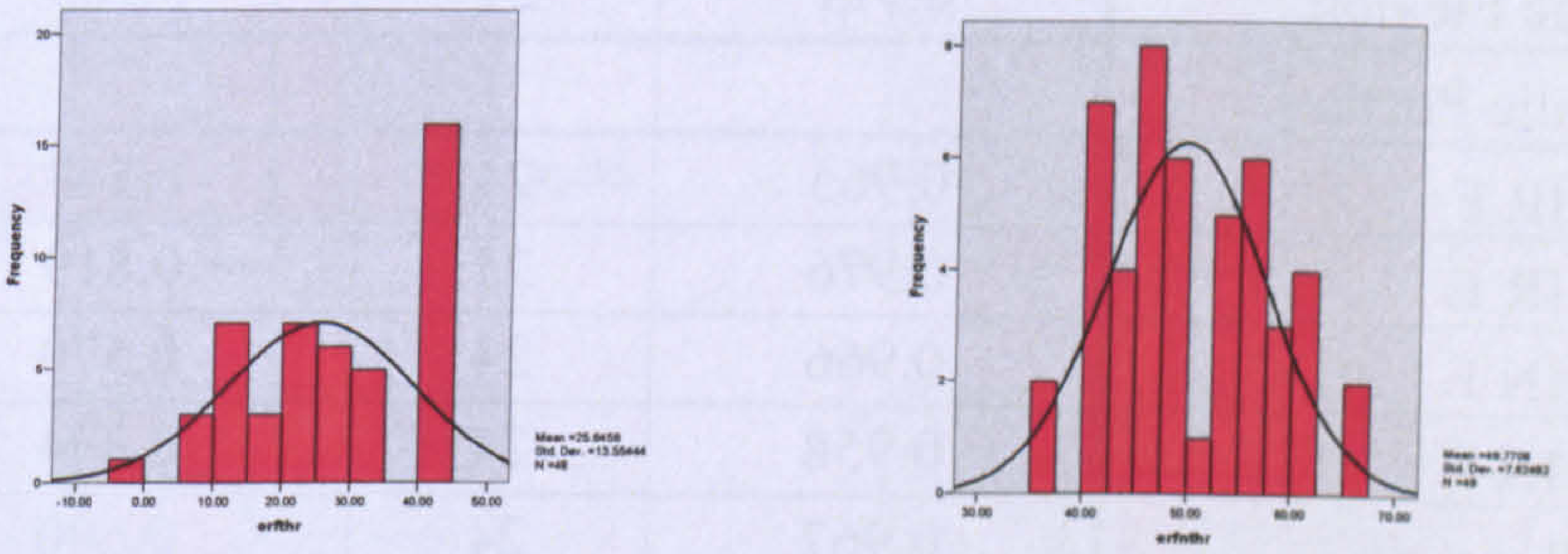
Normal Distribution Graphs: Physiological Hip Movement – Sagittal and Frontal Planes



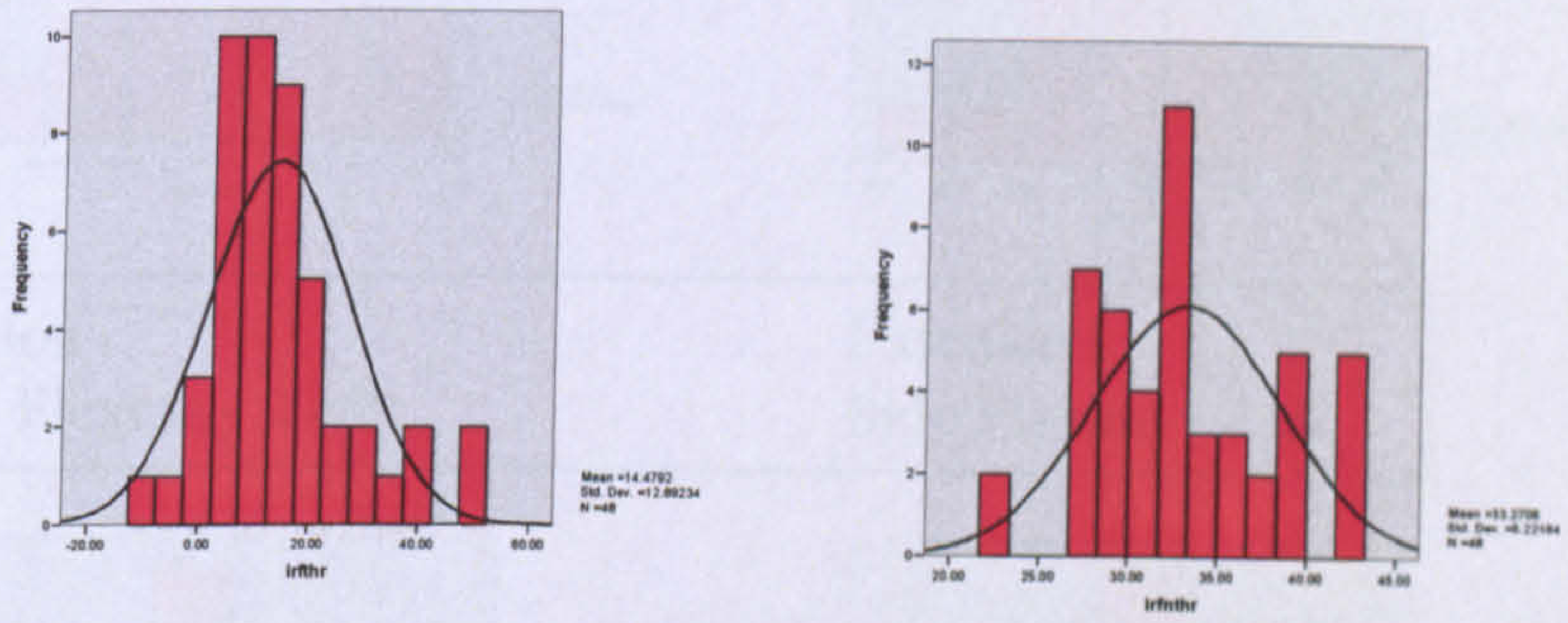
External rotation in Extension



Internal rotation in Extension



External rotation in 70° Flexion



Internal rotation in 70° Flexion

Normal Distribution Graphs: Physiological Hip Movement – Horizontal Plane
in Extension and 70° Flexion

C) Lumbar Spine

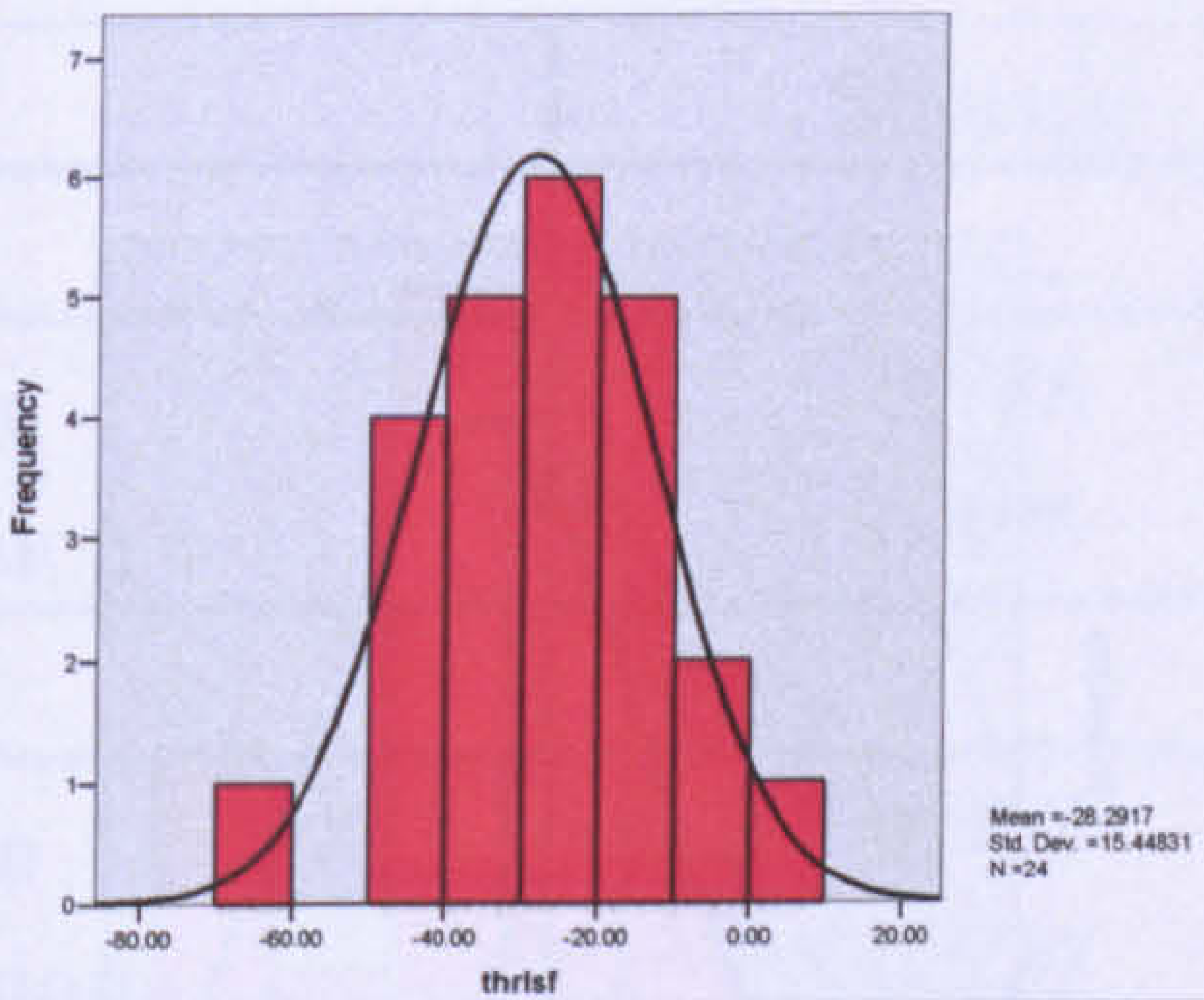
Shapiro-Wilk Test: Normal Distribution: Lumbar Spine movement in all Planes

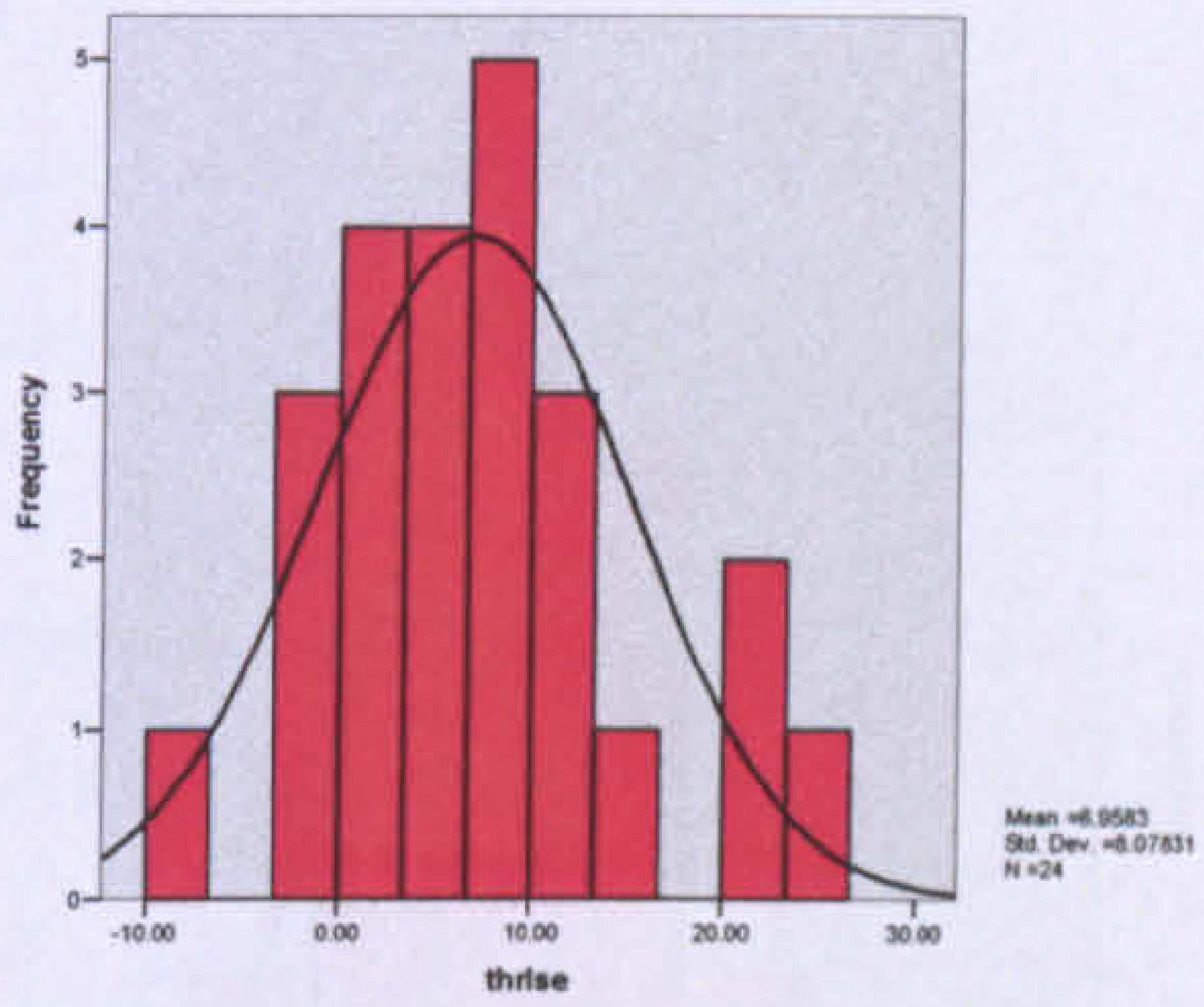
	Statistic	df	Significance
THR			
Flexion	0.992	24	0.999
Extension	0.931	24	0.102
Side Flexion Right	0.956	24	0.366
Side Flexion Left	0.976	24	0.812
Side Flexion	0.956	24	0.366
Non-THR			
Flexion	0.958	24	0.401
Extension	0.969	24	0.638
Side Flexion Right	0.971	24	0.703
Side Flexion Left	0.941	24	0.169
Side Flexion	0.971	24	0.703
Static Posture			
THR F	0.965	24	0.543
THR E	0.976	24	0.819
THN F	0.966	24	0.570
THN E	0.958	24	0.394
All	0.967	24	0.600

All data normally distributed

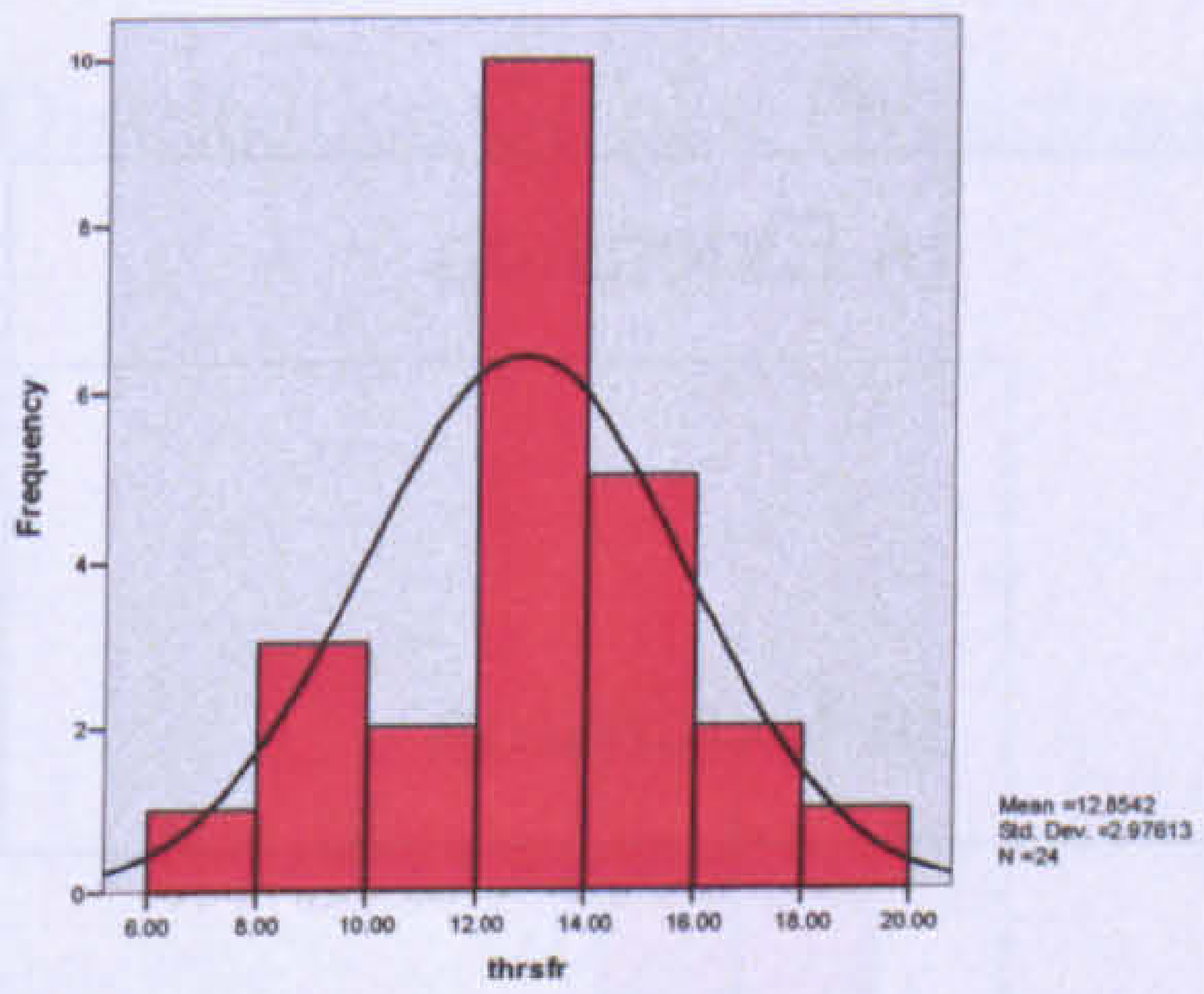
Normal distribution Graphs: Lumbar Spine Physiological Movement

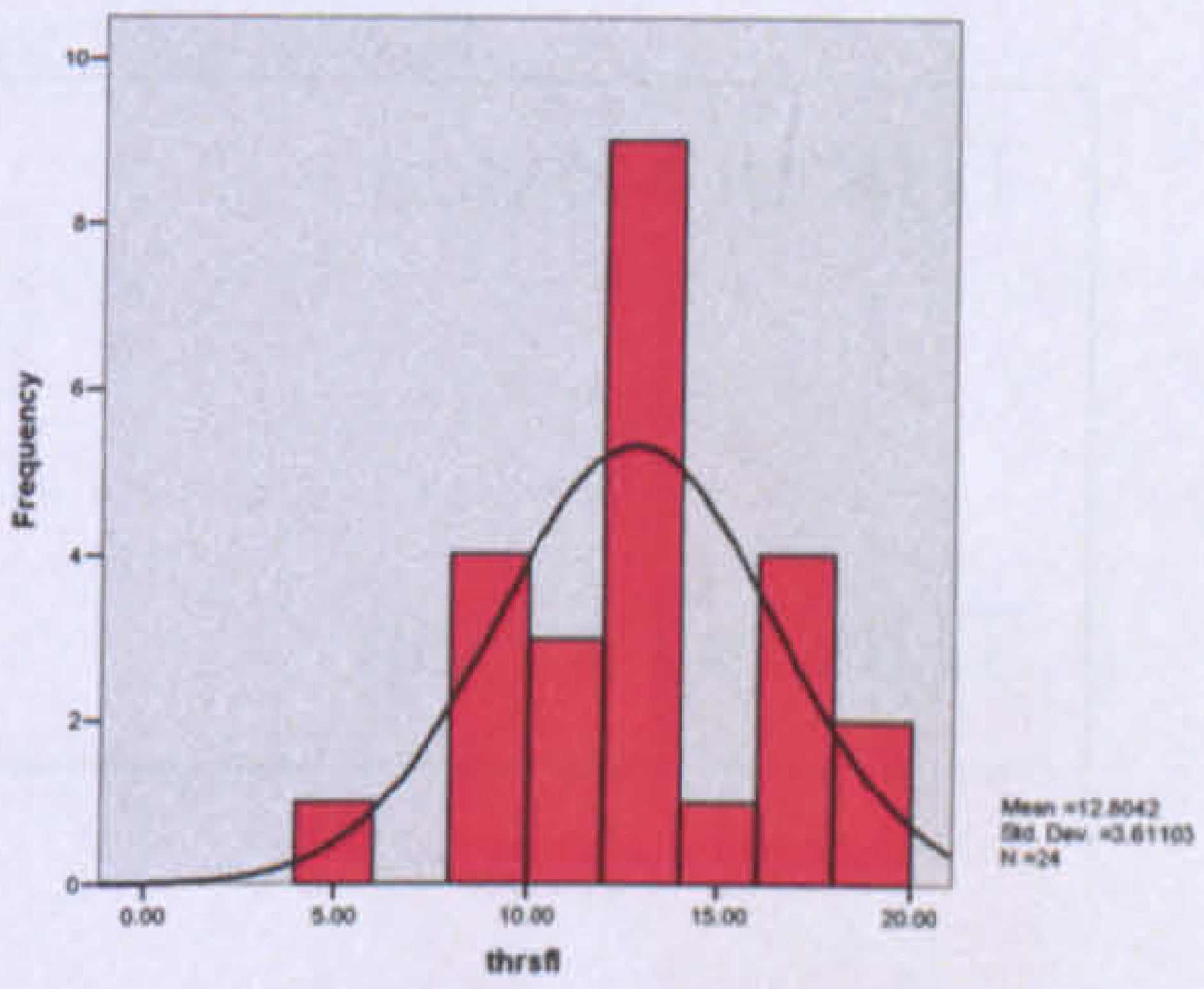
THR



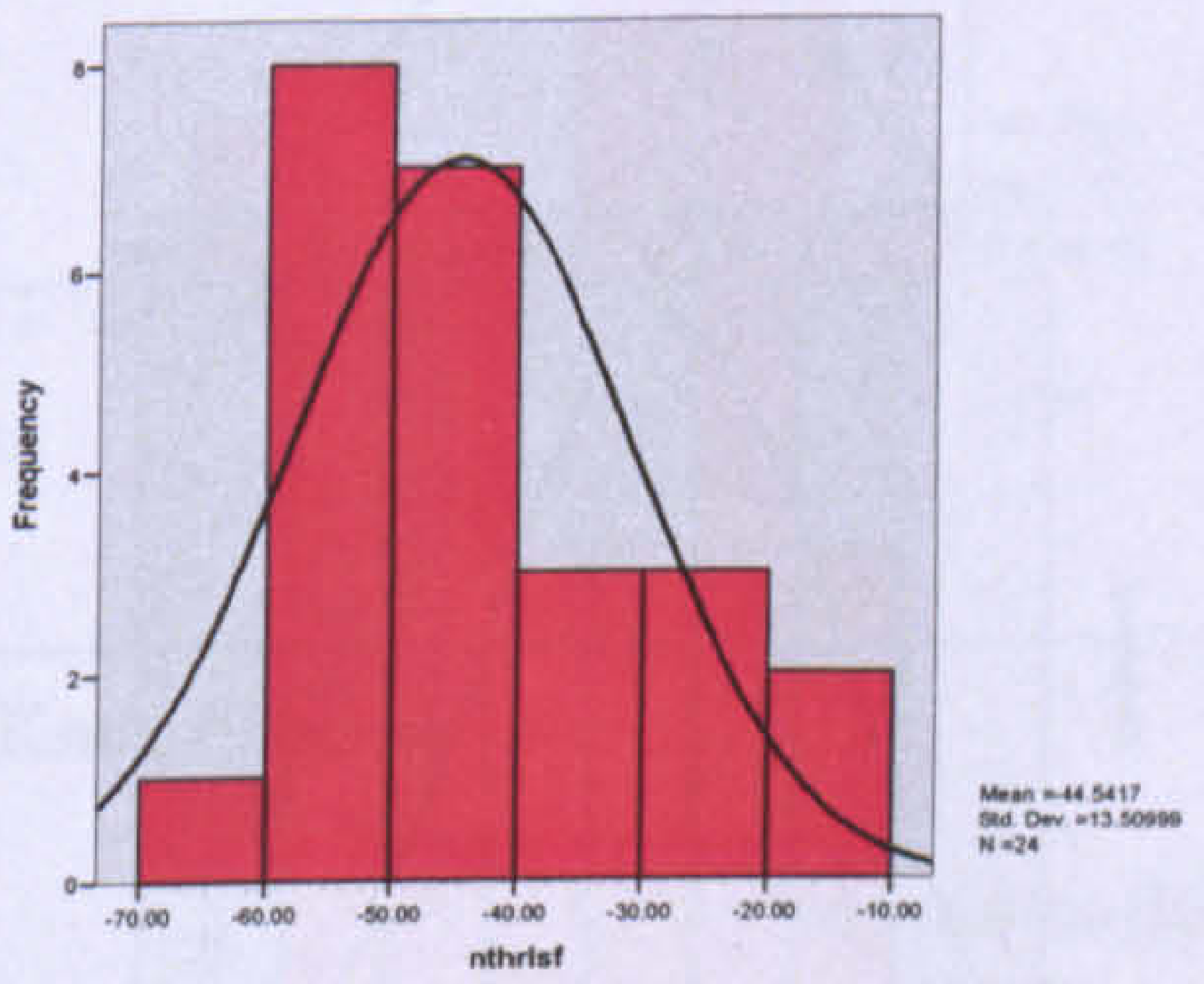


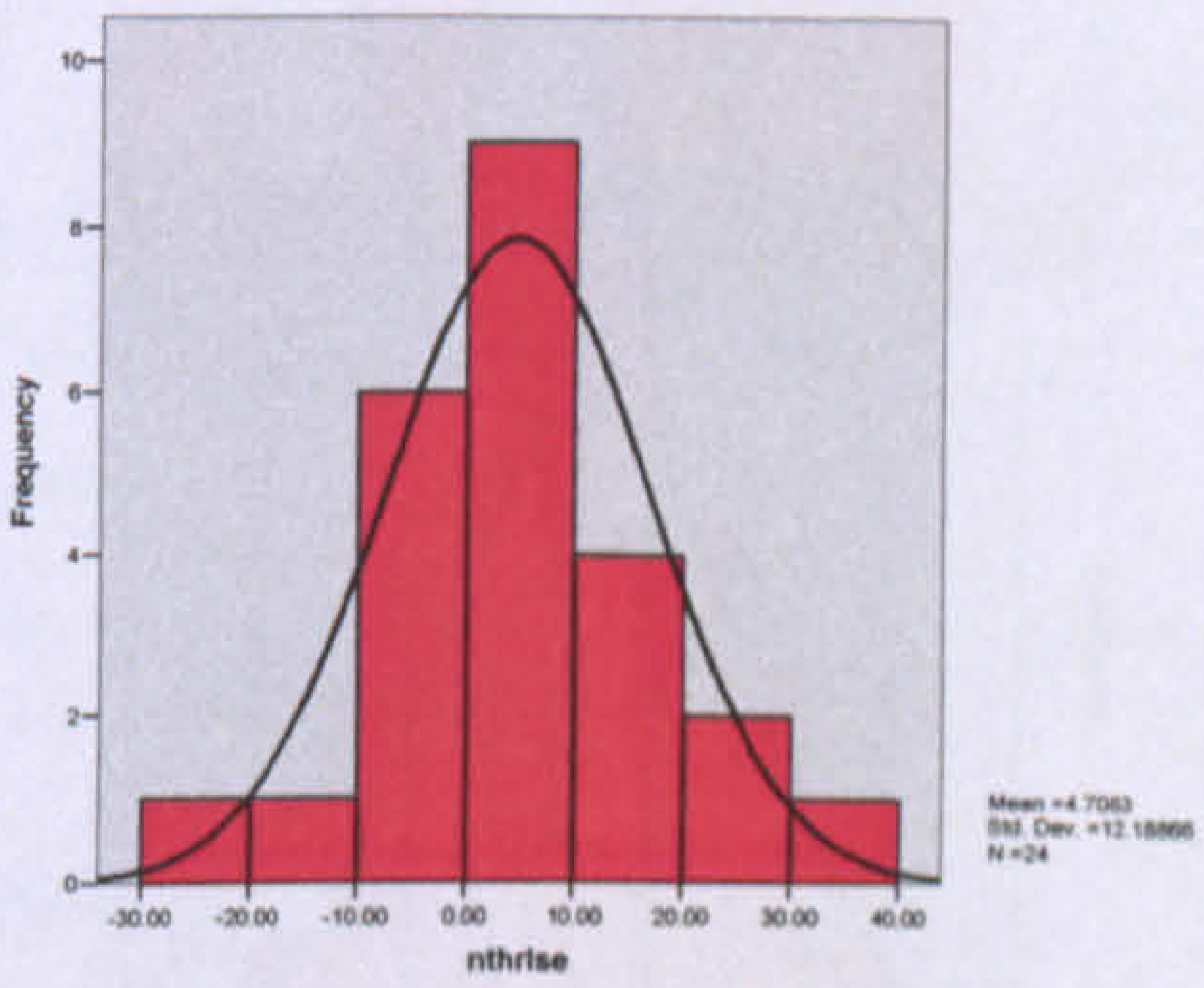
Flexion Side Flexion - Right	Extension Side Flexion - Left



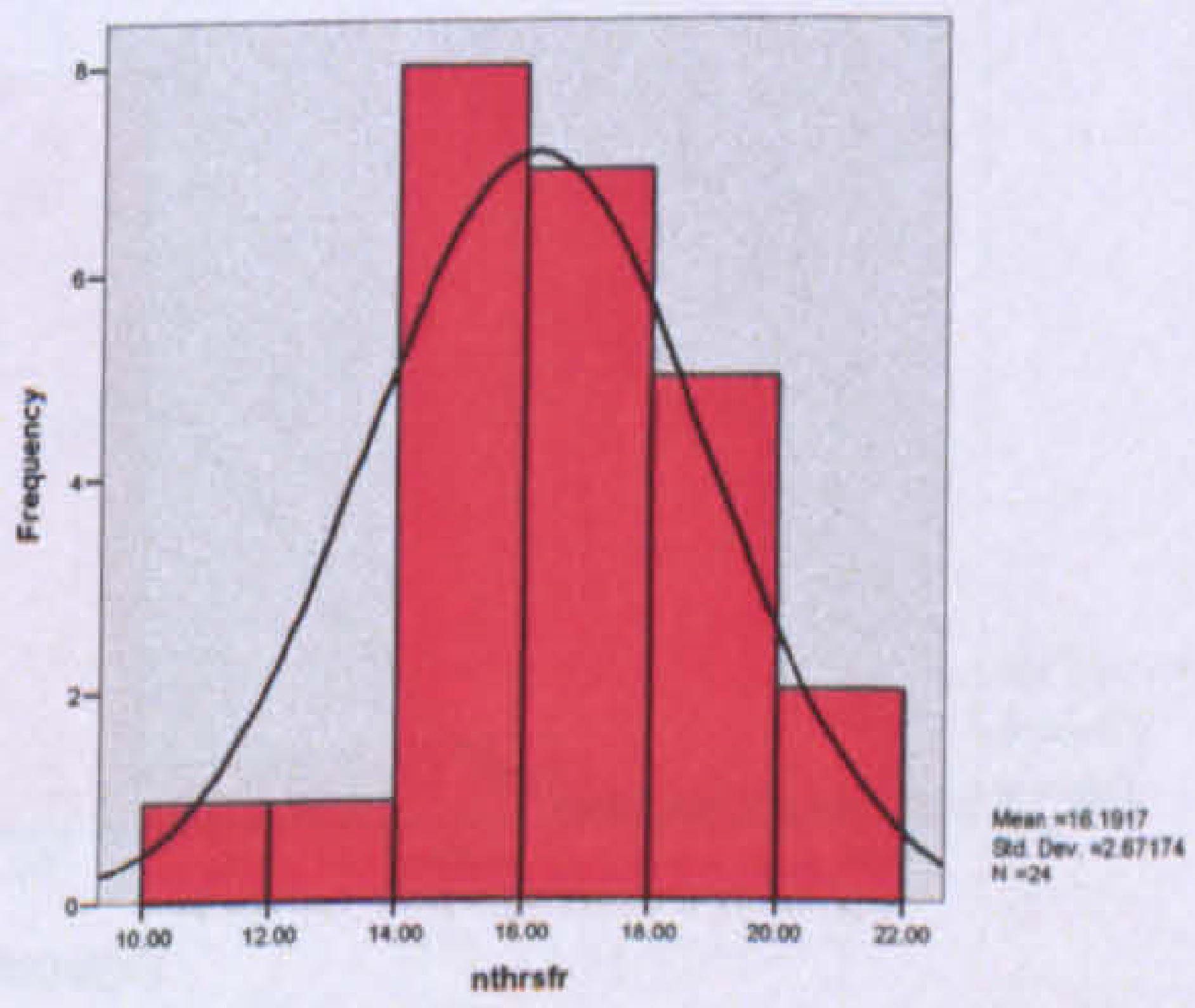


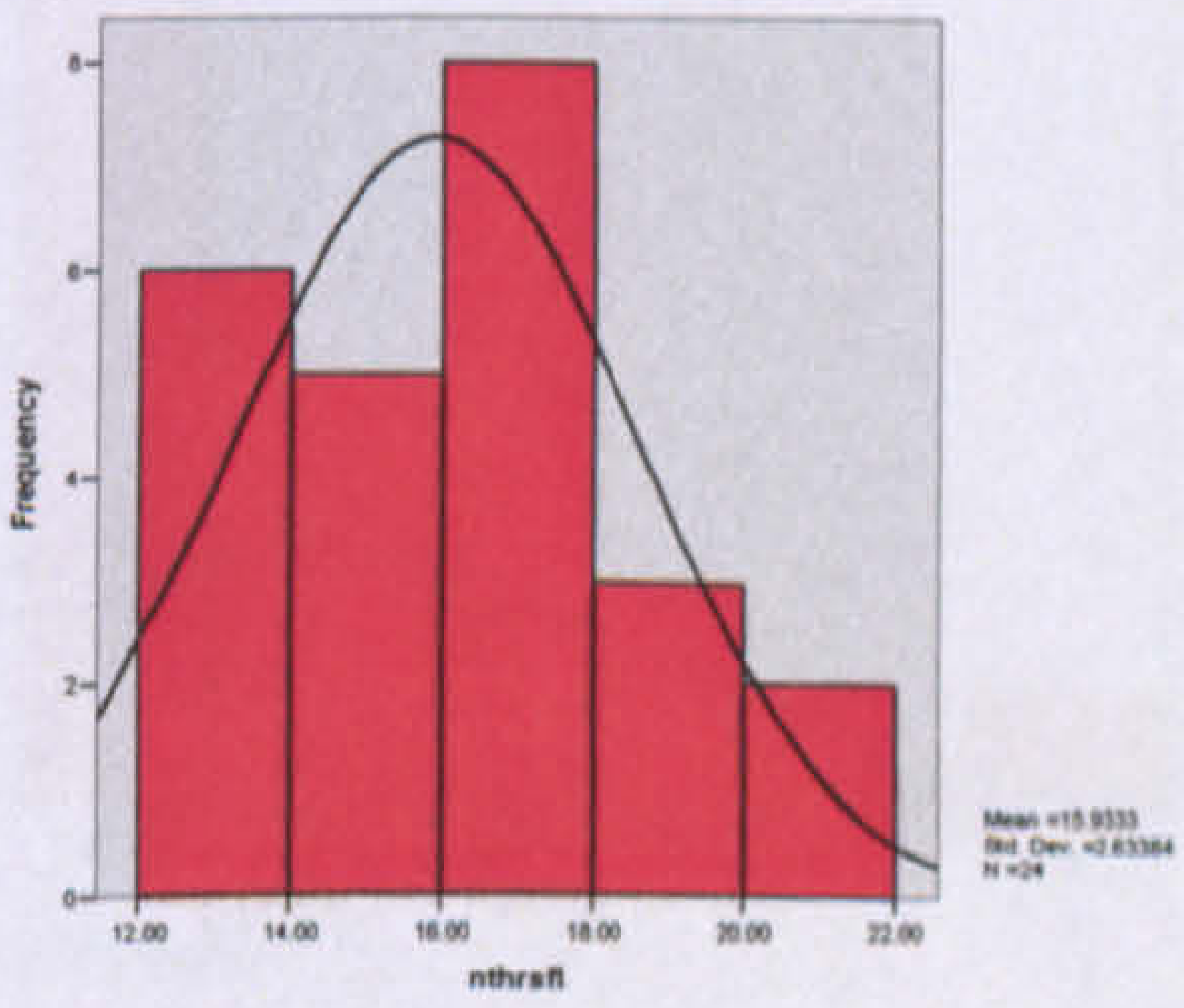
THN



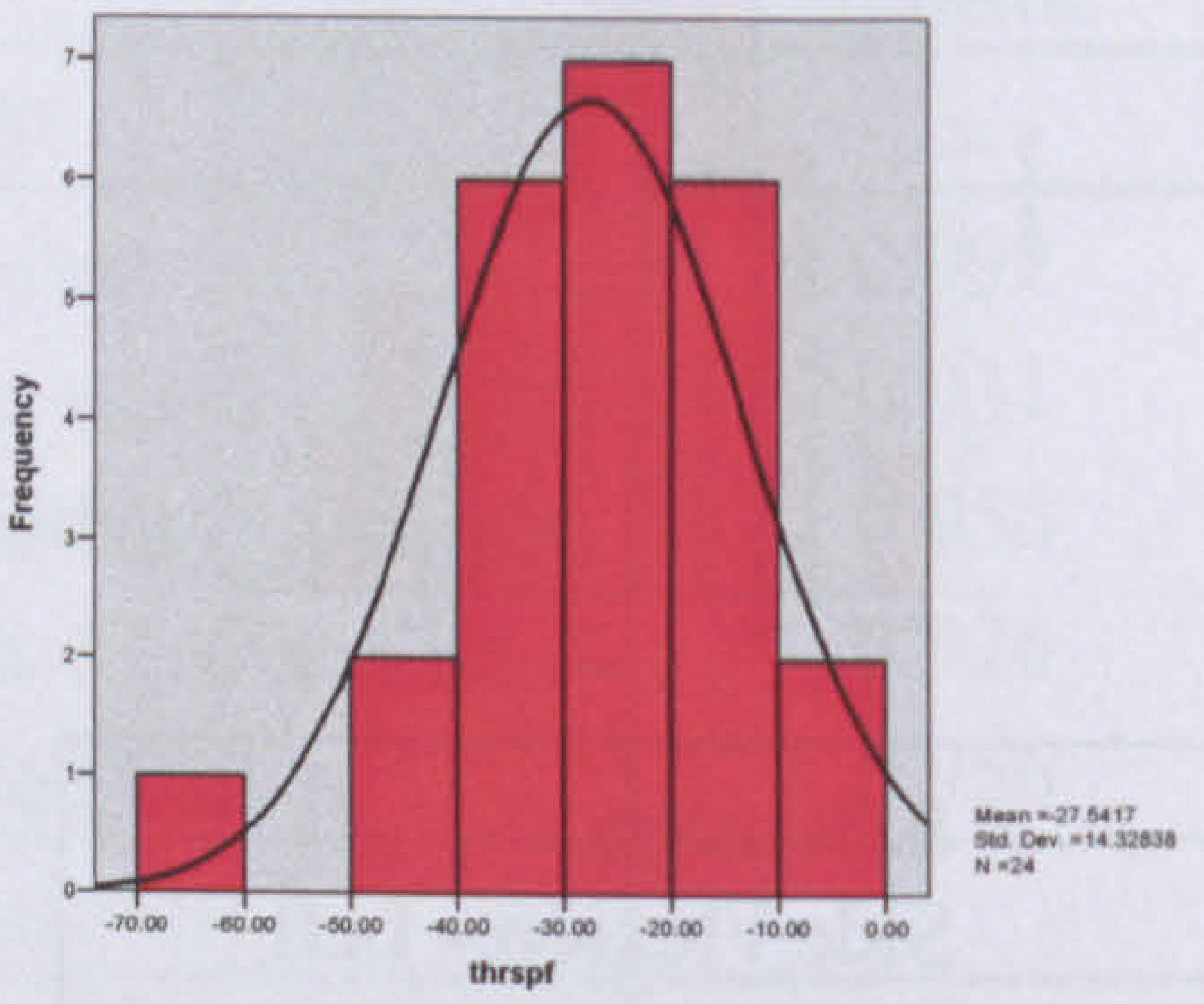


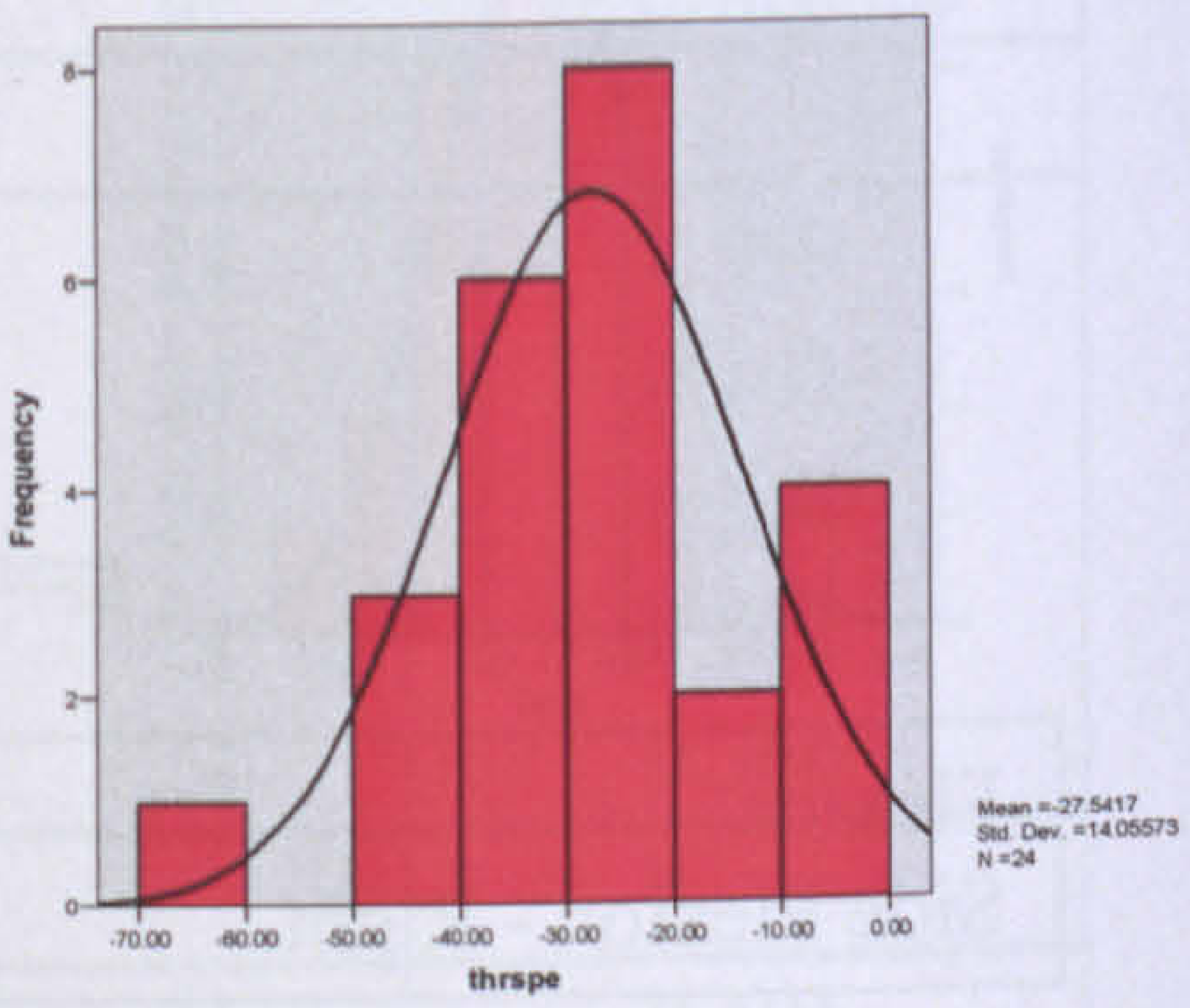
Flexion Side Flexion - Right	Extension Side Flexion - Left



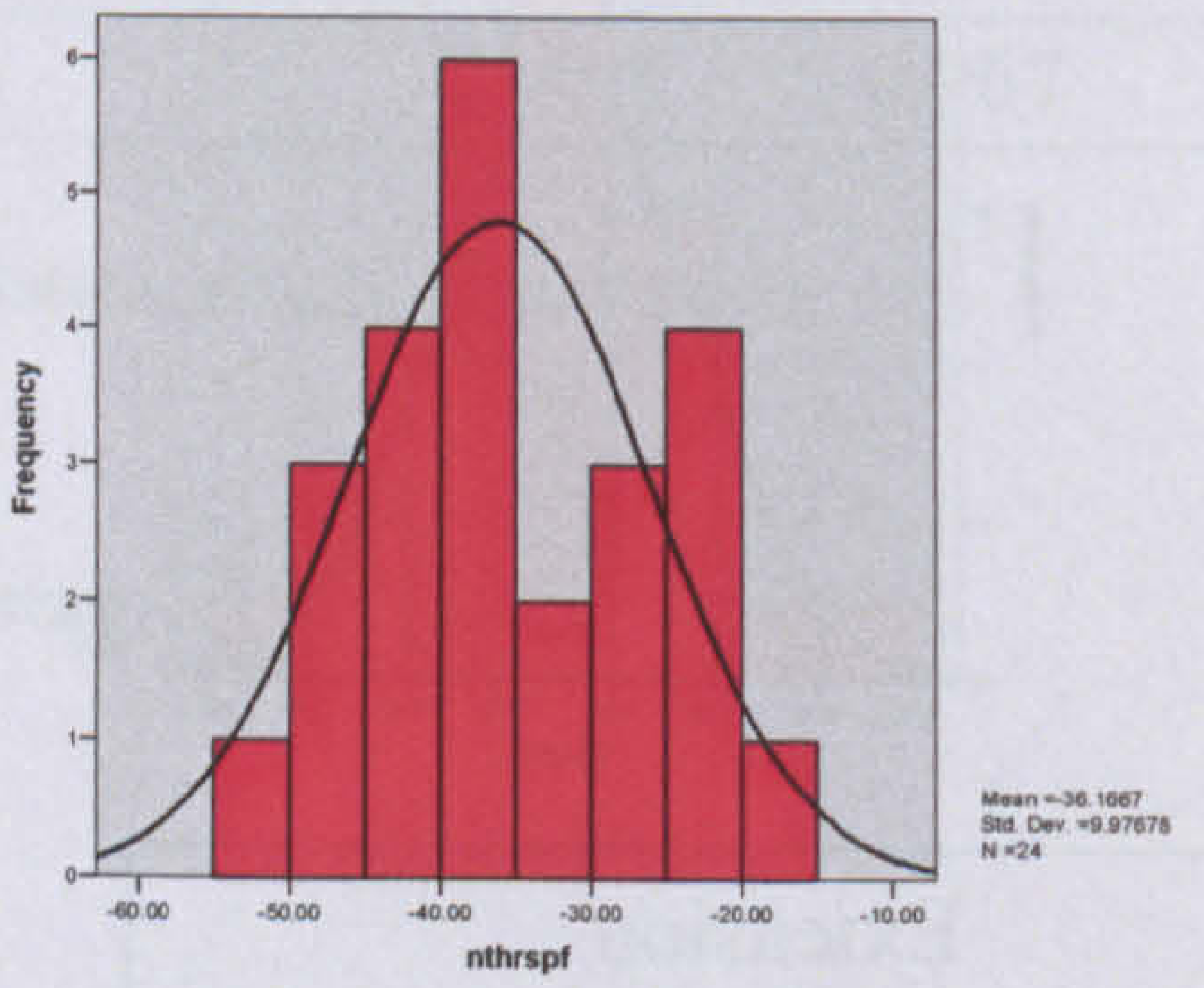


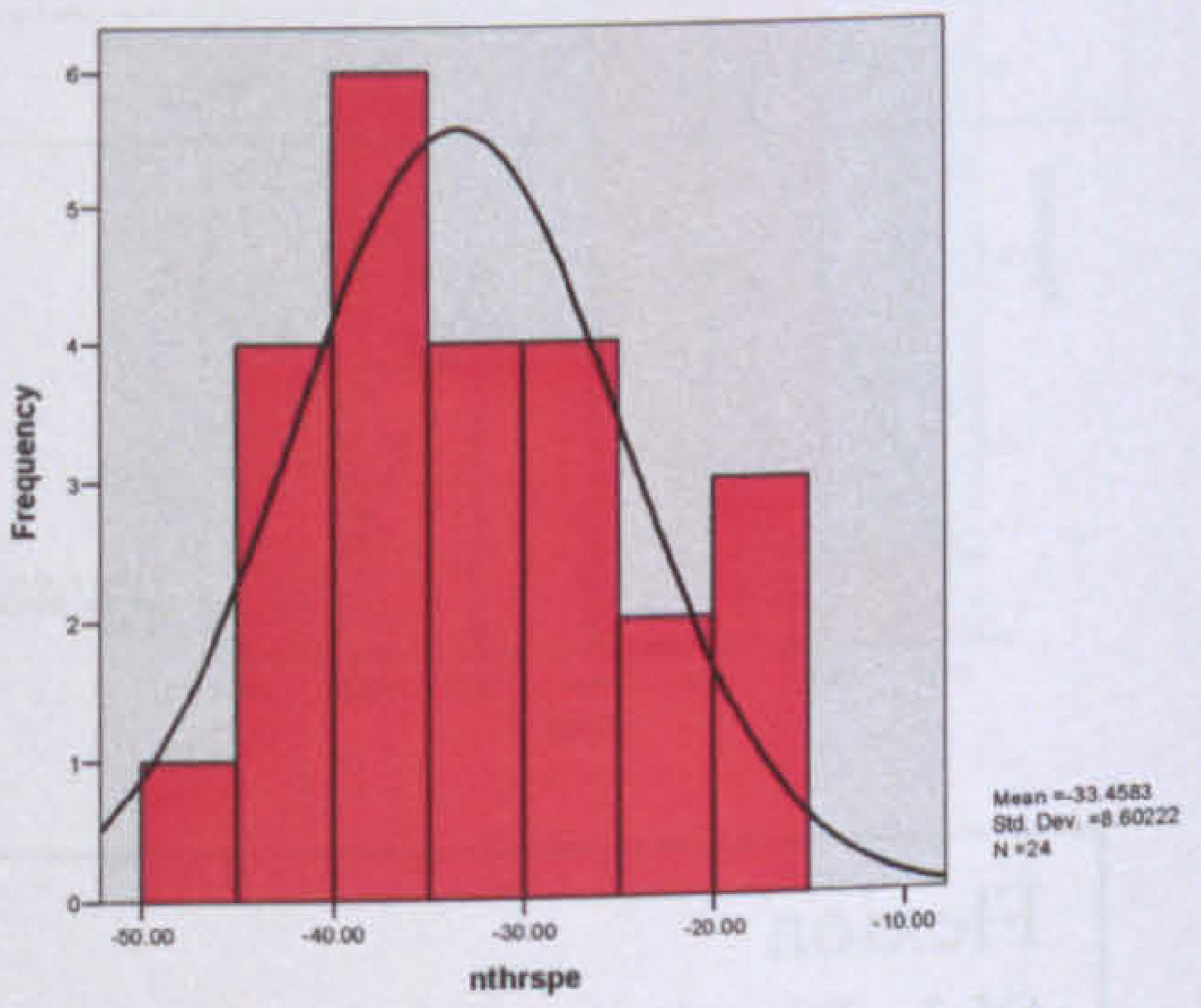
Static Lumbar Spine Position





THR in Flexion	in Extension
THN in Flexion	in Extension





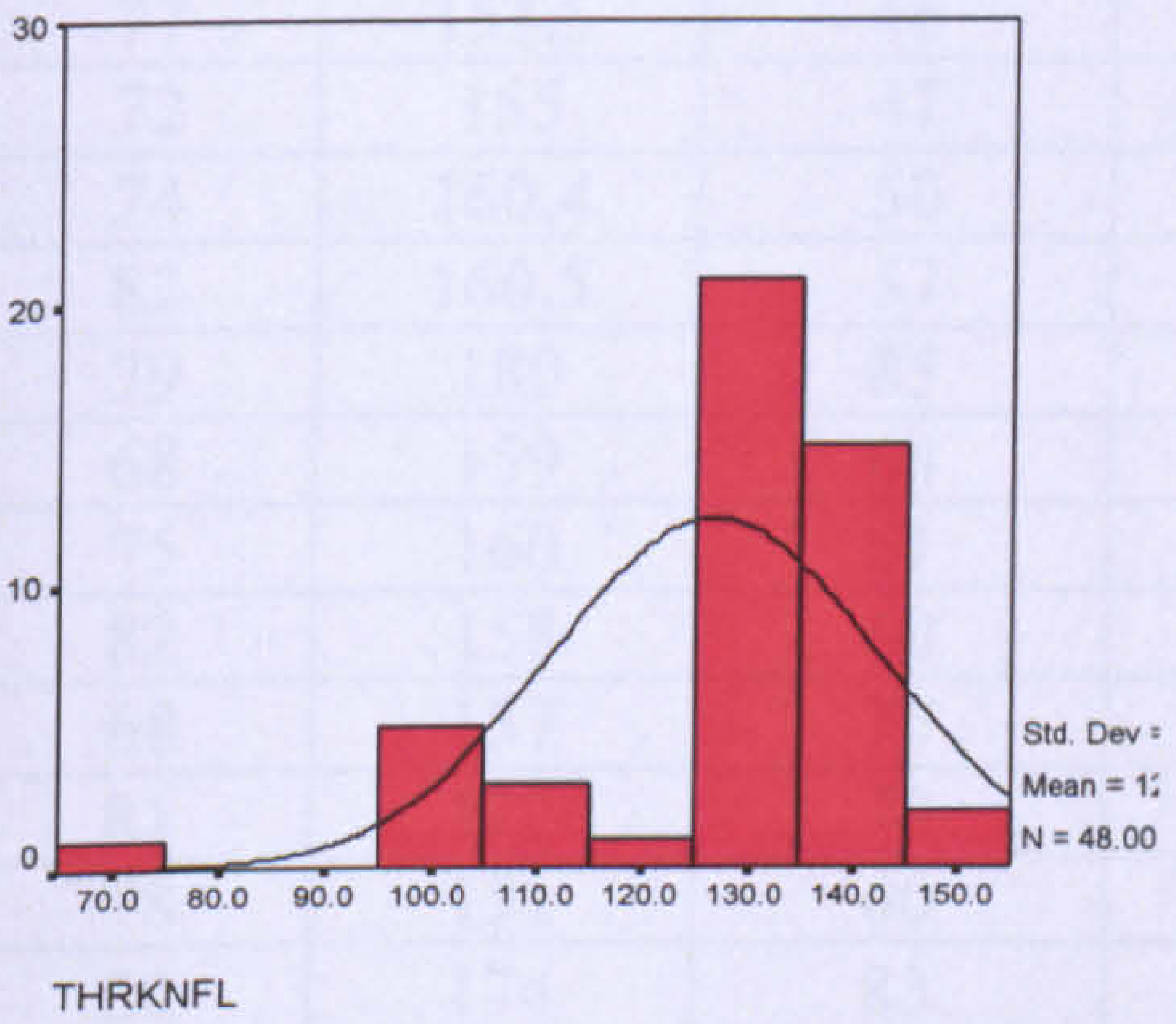
D) Knee Movement

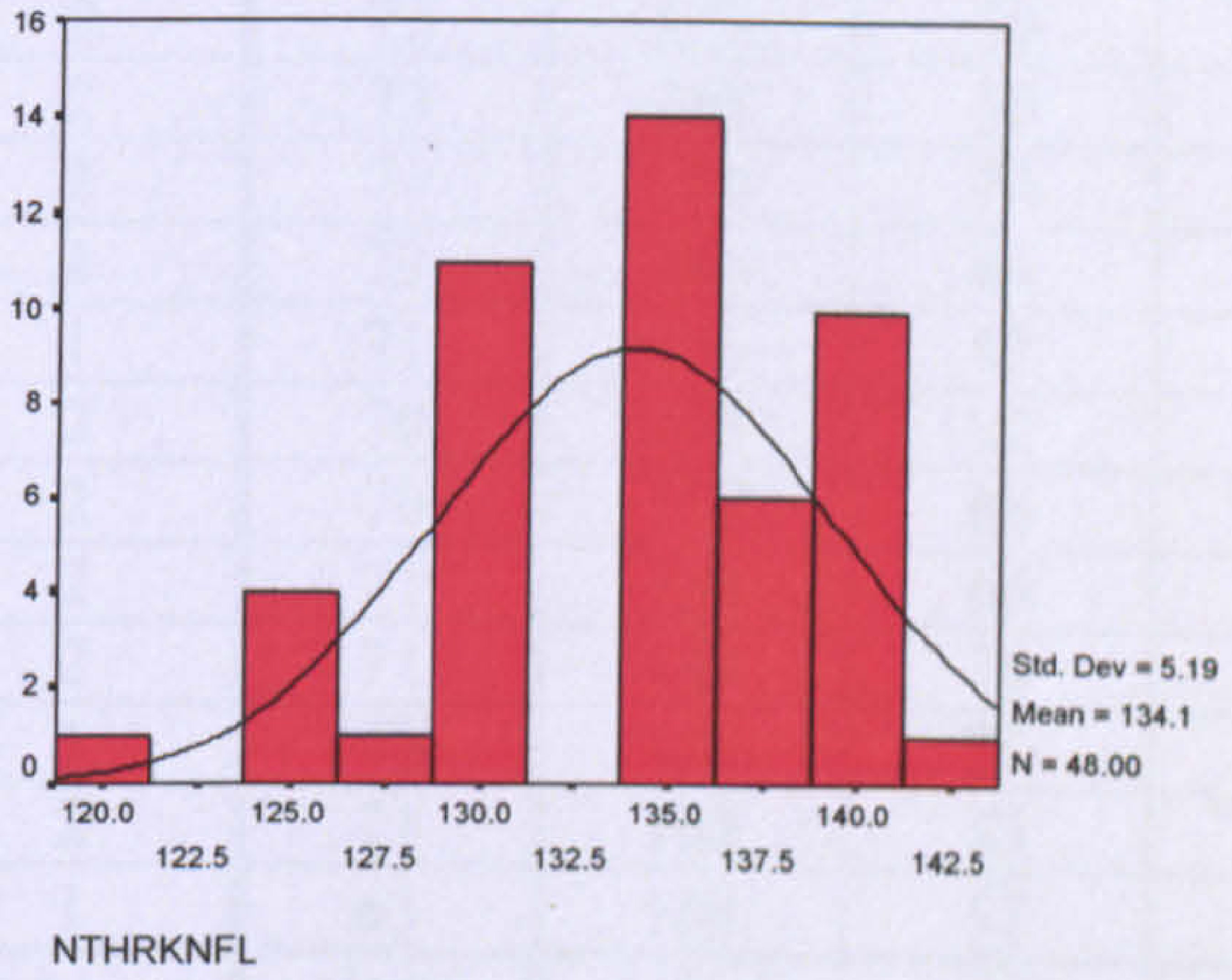
Shapiro-Wilk Test: Normal Distribution: Knee movement in the Sagittal Plane

	Statistic	Df	Significance
THR			
Flexion Extension	0.788 0.495	48 48	0.000 0.000
THN			
Flexion Extension	0.958 0.579	48 48	0.082 0.000

Only Knee flexion in the non hip replacement group is normally distributed.

Normal Distribution Graphs: Physiological Knee Movement

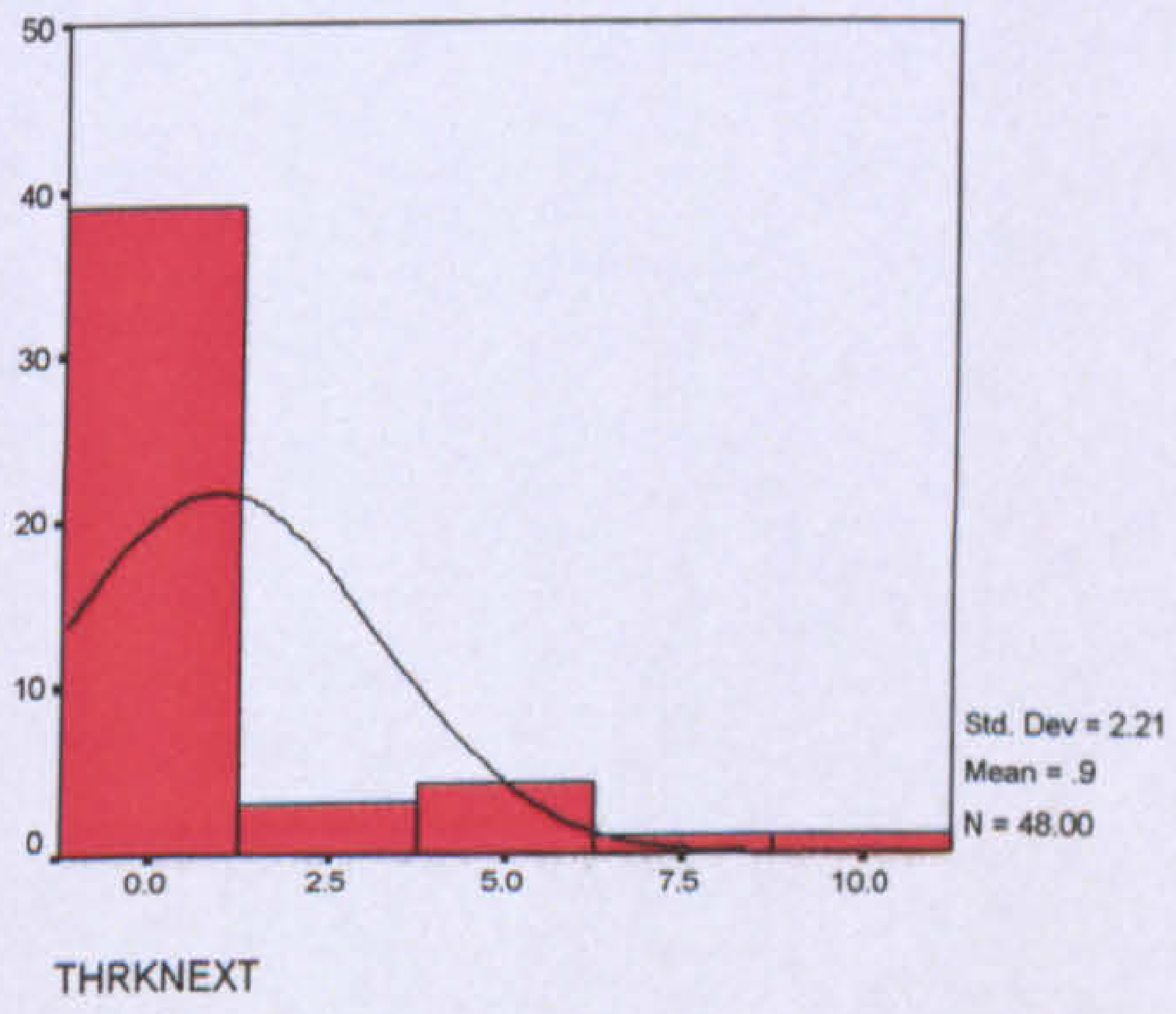


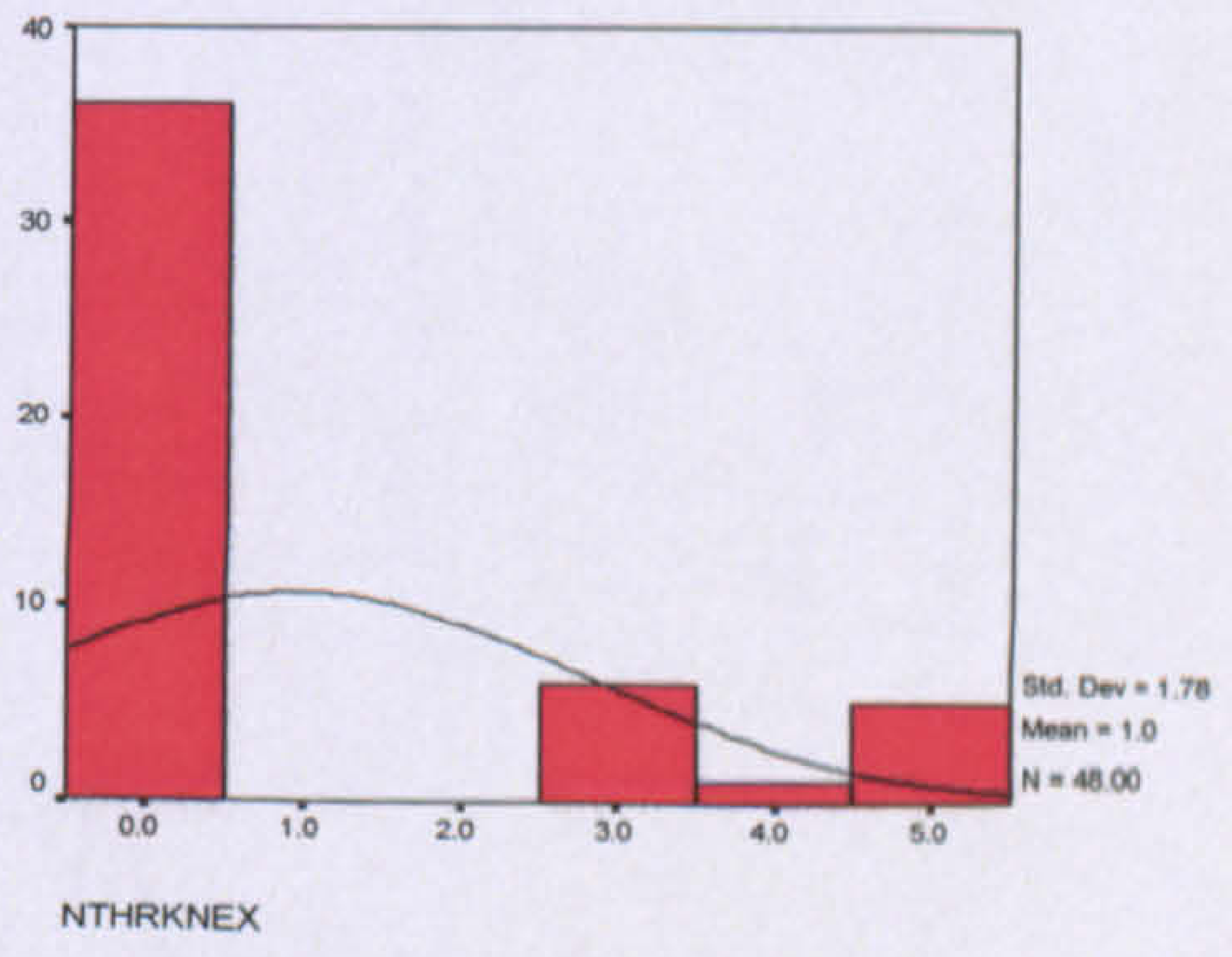


THR Knee Flexion *
THN Knee Flexion

= Not normally distributed

THR Knee Extension*
THN Knee Extension*





Appendix M: Demographic Data

A) Raw Data

THR				THN			
Age (yrs)	Height (cm)	Weight (kg)	Gender M=1, F=2	Age (yrs)	Height (cm)	Weight (kg)	Gender M=1, F=2
77	157	45	2	71	170	93	1
75	169	80	1	73	166.5	64	2
75	160.5	71	2	72	170	80	1
70	151.5	64	2	78	178	73	1
66	155.4	67	2	81	156	55	2
69	149.5	58	2	74	185	75	1
72	166.4	65	2	77	178	60	1
71	153.5	48	2	72	159	60	2
72	152.5	52	2	83	157	64	2
72	157	62	2	78	156	60	2
79	163	76	2	72	156	58	2
71	166.2	73	1	73	164	70	2
77	153.5	46	2	72	171	70	1
72	155	47	2	73	168	50	2
74	160.4	50	2	71	158	74	2
82	160.5	57	2	73	166	64	2
79	180	85	1	71	156	52	1
68	159	64	2	70	175	92	1
75	160	61	2	70	157	65	2
82	158	60	2	71	153	66	2
68	157	75	2	71	164	76	2
81	177	70	1	73	154	58	2
78	151	60	2	71	155	53	2
80	174	83	1	63	164	57	2
74.81	160.75	64.62	Mean	73.04	164.02	66.21	Mean
4.89	8.06	12.29	SD	4.05	8.89	11.42	SD

B) Statistical Analysis

Independent Ttest between all participants in THR and THN group.

Age

Independent Samples Ttest: Equal variances assumed

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
1.053	46	.298	1.33	1.27	-1.21	3.88

Height

Independent Samples Ttest: Equal variances assumed

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
-1.515	46	.137	-.04	.025	-.087	.012

Weight

Independent Samples Ttest: Equal variances assumed

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
-.871	46	.39	-2.92	3.35	-9.66	3.82

Calculation of Chi squared analysis for gender differences per group

Groups	Males	Females	Totals
THR	5	19	24
THN	8	16	24
	13	35	48

Chi squared formula:

$$\chi^2 = \frac{N\left[(AD-BC) - N/2\right]^2}{(A+B)(C+D)(A+C)(B+D)}$$ (Hicks, 1997)

Where

AD	80
BC	152
A+B	24
C+D	24
A+C	13
B+D	35

$$= \frac{442368}{262080}$$

$\chi^2 = 1.6879$, $p > 0.05$

Two-way ANOVA for group and gender

Age

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	12.800	1	12.800	1.03	.368
Error (GROUP)	49.700	4	12.425		
Gender	9.800	1	9.800	.31	.608
Error (GENDER)	126.700	4	31.675		
Group * gender	96.800	1	96.800	4.22	.109
Error (GROUP*GENDER)	91.700	4	22.925		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	112800.200	1	112800.200	36682.992	.000
Error	12.300	4	3.075		

Height

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	62.658	1	62.66	10.81	.03
Error(GROUP)	23.192	4	5.79		
Gender	1598.472	1	1598.47	22.98	.009
Error(GENDER)	278.278	4	69.57		
Group * gender	1.682	1	1.68	.099	.77
Error(GROUP*GENDER)	67.968	4	16.99		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	549660.168	1	549660.17	29638.466	.07
Error	74.182	4	18.546		

Weight

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	7.200	1	7.200	.065	.812
Error(GROUP)	444.300	4	111.075		
Gender	1344.800	1	1344.800	15.123	.018
Error(GENDER)	355.700	4	88.925		
Group * gender	3.200	1	3.200	.039	.853
Error(GROUP*GENDER)	326.300	4	81.575		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	95220.000	1	95220.000	4978.824	.000
Error	76.500	4	19.125		

Males versus Females

Independent Samples Ttest: Equal variances not assumed

THR group: Height

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
-6.008	5.343	.001	-16.36	2.72	-23.23	-9.49

Independent Samples Ttest: Equal variances not assumed

THN group: Height

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
-4.075	9.440	.003	-13.28	3.26	-20.60	-5.96

Independent Samples Ttest: Equal variances not assumed

THR Group: Weight

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
-5.210	9.164	.001	-18.83	3.61	-26.99	-10.68

Independent Samples Ttest: Equal variances not assumed

THN Group: Weight

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Dierence	
					Lower	Upper
-2.292	8.844	.048	-12.25	5.34	-24.37	-.13

Appendix N: Operation details and answers to function questions

1) Operation and function details
2) Hobbies
3) Leg Length

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1) Operation and function details: Raw & Summary Data

a) Total Hip replacement Group (THR)

Op leg R=1, L=2	Time since op (months)	Walking Aids	Hip Pain R=1, L= 2, No pain = 0	VAS Hip	Back Pain Y=1, N=0	VAS LBP	Stairs Y=1, N=0
2	25	1 stick out	0		1	2	1
2	43	0	0		0		1
1	36	1 stick out	0		1	2	1
1	29	0	1	2	1	1	1
1	25	0	0		1	2	1
2	28	0	0		1	1	1
1	27	1 stick out	0		1	2	1
2	42	1 stick out	1	1	1	2	1
2	27	0	0		0		1
1	20	0	0		0		1
1	21	1stick out	1	1	1	3	1
1	32	0	0		0		1
1	32	0	0		1	1	1
2	20	1stick out	0		0		1
1	22	0	1	1	1	2	1
1	21	0	0		1	1	1
1	22	0	0		1	2	1
1	24	0	0		1	2	1
2	34	0	0		1	1	1
1	22	0	0		0		1
1	49	1 stick out	0		0		1
1	20	0	0		0		1
2	21	0	0		0		1
2	22	1 stick out	0		1	2	1
R = 15 L = 9	Mean = 27.67 SD = 8.11 Min = 20 Max = 49	1stick = 8 0 = 16	R = 4 L = 0 No pain = 20	Mode = 1 Range = 1 - 2	Y = 15 N = 9	Mode = 1 Range = 1-3	Y = 24 N = 0

Key: out = outside, R = Right, L = Left, Y = Yes, N= No

Comparison of previous surgery between groups (n = 48)

Previous Surgery	Non-THR (n=24)	THR (n=24)
Heart Bypass	2	0
Total Knee Replacement	0	4
Hysterectomy	4	4
Hernia repair	0	2
Mastectomy	2	0
Colostomy	1	0
Cataract removal	0	4
Lumpectomy	1	1
Goitre	0	1
Cholecystectomy	2	0

Comparison of medical problems between groups (n = 48)

Problems	non-THR (n = 24)	THR (n = 24)
No problems	12	2
Low Back Pain	1	15
OA hands, feet	2	6
OA Knees	3	2
High Blood Pressure	1	5
Eyes	0	5
Dizzy	0	3
Cancer	1	2
Diabetes	0	2
Heart	2	1
Respiratory	1	1
Deep Vein Thrombosis	0	1
Hiatus Hernia	0	1
Hypertrophic ossification	0	1
Osteoporosis	0	1
Sleep	1	0

b) Non-Total Hip replacement Group (Non-THR)

Walking Aids Y=1, N=0	Hip Pain Y=1, N=0	Hip Pain R=1, L = 2	Back Pain Y=1, N=0	Stairs Y=1, N=0
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	0	1
0	0	0	1	1
0	0	0	0	1
Y = 0	Y = 0	R = 0	Y = 1	Y = 24
N = 24	N = 24	L = 0	N = 23	N = 0

Key: R = Right, L = Left, Y = Yes, N= No

2) Hobbies

Calculation of Chi squared analysis for hobbies between the groups

Leisure Pursuits	Passive	Active	Totals
THR group	21	11	32
Non THR group	8	32	40
Totals	29	43	72

Formula:

$$\chi^2 = \frac{N\,[\,(AD\text{-}BC) - N/2\,]^2}{(A+B)(C+D)(A+C)(B+D)} \qquad \text{(Hicks, 1997)}$$

Where:

AD	672
BC	88
A+B	32
C+D	40
A+C	29
B+D	43

$$\frac{27676800}{1596160}$$

$\chi^2 = 13.55$, $p<0.0001$ OR $\chi^2 = 9.50$, $p<$

AD	561
BC	105
A+B	24
C+D	48
A+C	29
B+D	40

3) Leg Length

a) Raw Data THR Group
b) Raw Data non-THR Group
c) Leg Length - Statistical Analysis
d) Operated vs non-operated true leg length
e) Operated vs non-operated apparent leg length

a) Raw Data THR Group

THR	True Leg length		Apparent Leg length		True	Apparent
All data cm	R	L	R	L	diff R-L	diff R-L
	79.5	81.25	105	108.5	-1.75	-3.5
	87.5	87.5	114	113	0	1
	85.5	86	106.5	106.5	-0.5	0
	83.5	84	105	105	-0.5	0
	78.5	78.8	105	105.2	-0.3	-0.2
	75.2	75	104.2	104	0.2	0.2
	90.5	91	113	114	-0.5	-1
	80	82	106	108	-2	-2
	86	86	111	111	0	0
	82.5	83	109	108	-0.5	1
	83	81	114	113.5	2	0.5
	85	85	113.5	113.5	0	0
	82	82	105.5	105.5	0	0
	83.5	83	106.5	107	0.5	-0.5
	78	77	108	108	1	0
	85	85	109.5	109.5	0	0
	95	94.8	124	123.5	0.2	0.5
	87	87.2	114	113	-0.2	1
	84	84	108	108	0	0
	81	81	105	105	0	0
	88.5	89	109	111.5	-0.5	-2.5
	91	92	108	109	-1	-1
	81.5	81.5	105	104	0	1
	87	86.5	119.5	121	0.5	-1.5
Mean	84.18	84.31	109.51	109.80	-0.14	-0.29
SD	4.54	4.61	5.04	4.98	0.80	1.13
Min	75.2	75	104.2	104	-2	-3.5
Max	95	94.8	124	123.5	2	1

b) Raw Data non-THR Group

Non-THR	True Leg length		Apparent Leg length		True	Apparent
All data cm	R	L	R	L	diff R-L	diff R-L
	86	86.2	108	108.4	-0.2	-0.4
	86	86.2	108	108.4	-0.2	-0.4
	88	88	108.2	108	0	0.2
	92.5	92.5	116.7	116.3	0	0.4
	78.5	78.5	102.7	103	0	-0.3
	100	99	120	120	1	0
	92	92	117	117	0	0
	87	86	109	109	1	0
	82.6	82.5	104.6	104	0.1	0.6
	83	83	103	103	0	0
	81.5	81.5	104	104	0	0
	86	86	112	112	0	0
	89	89	109	109	0	0
	90	90	116	116	0	0
	82	82.2	104	104.2	-0.2	-0.2
	81.1	81	103.1	103	0.1	0.1
	86.3	86.3	106	106	0	0
	91	91	114	114	0	0
	81.6	81.6	106.5	106	0	0.5
	79.6	79.4	99.6	99.4	0.2	0.2
	85	85	107.5	107.3	0	0.2
	80	80	106	106	0	0
	78.4	78.5	99	99	-0.1	0
	85.8	85.5	106	106	0.3	0
Mean	85.54	85.45	107.91	107.88	0.08	0.04
SD	5.18	5.06	5.54	5.54	0.30	0.24
Min	78.4	78.5	99	99	-0.2	-0.4
Max	100	99	120	120	1	0.6

c) Leg Length - Statistical Analysis

Two way ANOVA between Groups and sides

True leg Length

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Groups	37.563	1	37.563	.782	.386
Error(GROUPS)	1104.538	23	48.023		
Side	1.898E-02	1	1.898E-02	.123	.729
Error(SIDE)	3.557	23	.155		
Groups * side	.298	1	.298	1.435	.243
Error(GROUPS*SIDE)	4.777	23	.208		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	691485.115	1	691485.115	15082.665	.000
Error	1054.466	23	45.846		

Apparent Leg Length

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Groups	74.378	1	74.378	1.328	.261
Error(GROUPS)	1288.135	23	56.006		
Side	.388	1	.388	1.097	.306
Error(SIDE)	8.125	23	.353		
Groups * side	.650	1	.650	2.048	.166
Error(GROUPS*SIDE)	7.302	23	.317		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1135850.305	1	1135850.305	20719.841	.000
Error	1260.847	23	54.819		

Paired sample Ttest to compare leg lengths between the operated and better legs.

Paired Samples Statistics

	Mean	N	SD	Std. Error Mean
True Leg Length				
Non-operated Leg	84.21	24	4.73	.97
Operated Leg	84.28	24	4.42	.90
Apparent Leg length				
Non-operated Leg	109.54	24	5.01	1.02
Operated Leg	109.77	24	5.01	1.02

Paired Samples Test: Differences between operated and better leg

Leg Length	Paired Differences					t	df	Sig. (2-tailed)
	Mean	SD	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
True	-0.07	0.81	0.16	-0.41	0.27	-0.44	23	0.66
Apparent	-0.23	1.15	0.23	-0.72	0.25	-0.996	23	0.33

d) Operated vs non-operated true leg length

True Leg length						
	non operated leg	operated leg	Difference R - L	**Left leg** Longer = L Shorter =S Equal = E	Op leg R=1 L=2	Operated Side
	79.5	81.25	-1.75	L	R	Short
	87.5	87.5	0	E	L	E
	86	85.5	0.5	L	R	Short
	84	83.5	0.5	L	R	Short
	78.8	78.5	0.3	L	R	Short
	75.2	75	0.2	R	L	Short
	91	90.5	0.5	L	R	Short
	80	82	-2	L	L	Long
	86	86	0	E	L	E
	83	82.5	0.5	L	R	Short
	81	83	-2	R	R	Long
	85	85	0	E	R	E
	82	82	0	E	R	E
	83.5	83	0.5	R	L	Short
	77	78	-1	R	R	Long
	85	85	0	E	R	E
	94.8	95	-0.2	R	R	Long
	87.2	87	0.2	L	R	Short
	84	84	0	E	R	E
	81	81	0	E	L	E
	89	88.5	0.5	L	R	Short
	92	91	1	L	R	Short
	81.5	81.5	0	E	R	E
	87	86.5	0.5	R	L	Short
Mean	84.21	84.28	-0.07			S=12
SD	4.73	4.42	0.80			E=8
Min	75.2	75	-2			L=4
Max	94.8	95	1			

e) Operated vs non-operated apparent leg length

Apparent Leg Length						
	non operated leg	operated leg	Difference R-L	**Left leg** Longer = L Shorter =S Equal = E	Op leg R=1 L=2	Operated Side
	105	108.5	-3.5	L	R	Short
	114	113	1	R	L	Short
	106.5	106.5	0	E	R	E
	105	105	0	E	R	E
	105.2	105	-0.2	L	R	Short
	104.2	104	0.2	R	L	Short
	114	113	-1	L	R	Short
	106	108	-2	L	L	Long
	111	111	0	E	L	E
	108	109	1	R	R	Long
	113.5	114	0.5	R	R	Long
	113.5	113.5	0	E	R	E
	105.5	105.5	0	E	R	E
	106.5	107	-0.5	L	L	Long
	108	108	0	E	R	E
	109.5	109.5	0	E	R	E
	123.5	124	0.5	R	R	Long
	113	114	1	R	R	Long
	108	108	0	E	R	E
	105	105	0	E	L	E
	111.5	109	-2.5	L	R	Short
	109	108	-1	L	R	Short
	104	105	1	R	R	Long
	119.5	121	-1.5	L	L	Long
Mean	109.54	109.77				S=7
SD	5.01	5.01				E=9
Min	104	104				L=8
Max	123.5	124				

Appendix O: Passive Physiological Hip movement

1) Raw Data (n = 24 per group (THR and THN)

a) Sagittal Plane Motion

	Flexion (Degrees)				Extension (Degrees)			
	THR		THN		THR		THN	
	Right	Left	Right	Left	Right	Left	Right	Left
	120	120	110	109	-15	0	10	9
	107	105	120	120	0	0	10	10
	80	90	100	105	5	0	5	8
	90	90	125	123	5	5	17	15
	90	110	115	113	0	0	10	10
	110	105	123	120	0	0	20	19
	90	110	120	121	0	0	21	20
	65	60	109	107	0	0	5	8
	95	95	112	110	0	0	17	15
	110	120	123	120	0	0	15	15
	80	95	115	117	5	0	17	16
	90	105	118	118	5	0	19	17
	100	115	120	122	0	0	21	20
	105	80	116	115	0	0	6	7
	100	108	125	125	0	0	16	17
	75	70	105	103	-5	-12	3	0
	100	105	107	105	0	0	4	7
	70	90	111	112	5	5	7	9
	115	110	103	106	0	0	5	5
	115	110	118	116	5	5	14	12
	110	120	123	121	0	0	20	22
	95	85	120	118	10	0	18	19
	120	125	130	128	0	0	19	15
	110	105	117	119	0	0	5	9
Mean	97.58	101.17	116.04	115.54	0.83	0.13	12.67	12.67
SD	15.58	16.26	7.61	6.99	4.58	3.08	6.36	5.62

e) Operated vs non-operated apparent leg length

Apparent Leg Length						
	non operated leg	operated leg	Difference R-L	Left leg Longer = L Shorter =S Equal = E	Op leg R=1 L=2	Operated Side
	105	108.5	-3.5	L	R	Short
	114	113	1	R	L	Short
	106.5	106.5	0	E	R	E
	105	105	0	E	R	E
	105.2	105	-0.2	L	R	Short
	104.2	104	0.2	R	L	Short
	114	113	-1	L	R	Short
	106	108	-2	L	L	Long
	111	111	0	E	L	E
	108	109	1	R	R	Long
	113.5	114	0.5	R	R	Long
	113.5	113.5	0	E	R	E
	105.5	105.5	0	E	R	E
	106.5	107	-0.5	L	L	Long
	108	108	0	E	R	E
	109.5	109.5	0	E	R	E
	123.5	124	0.5	R	R	Long
	113	114	1	R	R	Long
	108	108	0	E	R	E
	105	105	0	E	L	E
	111.5	109	-2.5	L	R	Short
	109	108	-1	L	R	Short
	104	105	1	R	R	Long
	119.5	121	-1.5	L	L	Long
Mean	109.54	109.77				S=7
SD	5.01	5.01				E=9
Min	104	104				L=8
Max	123.5	124				

THR sagittal plane motion by operated

	Flexion (Degrees)		**Extension (Degrees)**	
	THR non op side	THR op side	THR non op side	THR op side
	120	120	-15	0
	107	105	0	0
	90	80	0	5
	90	87	0	0
	110	90	0	0
	110	105	0	0
	110	90	0	0
	65	60	0	0
	95	95	0	0
	120	110	0	0
	105	90	0	5
	115	100	0	0
	105	80	0	0
	108	100	0	0
	75	70	-5	-12
	105	100	0	0
	90	70	5	5
	110	115	0	0
	115	110	5	5
	120	110	0	0
	85	95	0	10
	125	120	0	0
	110	105	0	0
	110	115	10	7
Mean	103.96	96.75	0.00	1.04
SD	14.87	16.27	4.17	3.99

b) Frontal Plane Motion

	Abduction (Degrees)				Adduction (Degrees)			
	THR		THN		THR		THN	
	Right	Left	Right	Left	Right	Left	Right	Left
	30	40	30	29	20	30	21	21
	30	25	30	30	10	10	35	34
	10	20	32	31	7	15	29	30
	10	15	35	36	10	10	32	31
	30	35	29	27	20	20	30	35
	40	30	40	41	0	0	31	30
	40	40	40	42	30	30	31	32
	15	15	28	27	15	15	27	26
	30	30	29	28	25	30	30	31
	40	40	40	30	30	30	37	40
	15	25	33	30	10	30	29	30
	25	35	30	34	30	30	29	28
	35	35	39	40	30	30	32	30
	40	35	32	33	30	20	29	27
	30	45	40	37	30	30	32	31
	30	12	30	28	20	20	28	28
	30	35	32	33	20	20	28	29
	30	35	33	36	40	40	30	29
	30	30	32	33	40	40	27	29
	35	20	31	30	40	30	27	26
	30	40	41	42	30	30	34	33
	20	20	40	36	30	30	28	30
	30	30	34	35	40	40	30	31
	40	20	29	28	10	10	27	28
Mean	28.96	29.46	33.71	33.17	23.63	24.58	29.71	29.96
SD	9.09	9.31	4.45	4.78	11.62	10.52	3.20	3.58

THR frontal plane motion by operated

	Abduction (Degrees)		**Adduction (Degrees)**	
	THR non op side	THR op side	THR non op side	THR op side
	30	40	20	30
	30	25	10	10
	20	10	15	7
	20	15	10	10
	35	30	20	20
	40	30	0	0
	40	40	30	30
	15	15	15	15
	30	30	25	30
	40	40	30	30
	35	25	30	30
	35	35	30	30
	40	35	30	20
	45	30	30	30
	30	12	20	20
	35	30	20	20
	35	30	40	40
	30	30	40	40
	35	20	40	30
	40	30	30	30
	20	20	30	30
	30	30	40	40
	40	20	10	10
	35	40	25	30
Mean	32.71	27.58	24.58	24.25
SD	7.66	8.93	10.83	10.96

c) Horizontal Plane Motion

1) Rotation measured in Extension

	External rotation in extension (Degrees)				Internal rotation in extension (Degrees)			
	THR		THN		THR		THN	
	Right	Left	Right	Left	Right	Left	Right	Left
	5	5	69	67	10	15	43	40
	40	25	76	76	10	20	50	50
	30	40	56	58	15	15	34	35
	25	15	77	73	10	10	58	59
	40	31	69	69	20	40	41	40
	30	35	79	76	40	45	52	50
	40	33	73	74	20	30	56	52
	20	15	65	64	12	25	50	48
	30	15	65	66	40	65	49	43
	20	15	78	78	28	22	57	56
	20	25	69	67	5	5	53	50
	25	32	69	66	20	32	48	43
	25	40	72	70	20	25	51	49
	50	39	67	65	10	20	56	55
	22	42	78	73	38	30	52	52
	20	30	59	64	0	0	53	50
	22	23	63	65	15	20	49	48
	34	30	66	66	15	40	41	40
	50	43	57	58	25	40	51	52
	37	35	70	68	27	27	56	55
	55	60	77	75	5	25	64	63
	30	30	74	74	5	-5	65	67
	25	35	79	77	30	30	67	66
	33	25	64	67	10	12	48	49
Mean	30.33	29.92	69.63	69.00	17.92	24.50	51.83	50.50
SD	11.51	11.85	6.91	5.62	11.37	15.32	7.68	8.13

2) Rotation Measured in 70° Flexion

	External Rotation (In 70° Flexion) (Degrees)				**Internal Rotation (In 70° Flexion) (Degrees)**			
	THR		THN		THR		THN	
	Right	Left	Right	Left	Right	Left	Right	Left
	25	10	40	41	5	10	29	28
	10	15	47	47	5	10	31	30
	10	10	35	36	5	5	32	33
	40	20	55	57	0	0	36	35
	15	45	40	40	5	15	28	28
	30	40	53	53	10	5	43	40
	30	40	55	56	15	20	39	38
	10	5	43	47	-10	15	23	22
	45	15	45	48	15	50	28	27
	30	40	53	53	15	20	43	43
	20	45	43	42	5	5	32	33
	10	30	46	45	15	10	33	32
	25	30	49	48	5	10	42	40
	40	29	42	40	10	25	35	36
	10	42	57	58	20	25	42	40
	5	-5	49	48	10	15	31	32
	20	40	43	44	5	10	30	31
	20	40	54	55	15	50	31	33
	25	25	46	47	40	40	29	27
	20	5	49	50	10	15	32	30
	40	40	60	59	30	30	39	38
	20	20	61	60	0	-5	32	33
	40	45	65	66	20	35	36	35
	40	25	59	60	10	20	29	28
Mean	24.17	27.13	49.54	50.00	10.83	18.13	33.54	33.00
SD	12.04	15.03	7.69	7.72	10.18	14.43	5.41	5.13

THR Horizontal Plane data by operated side

	External rotation in extension (Degrees)		**Internal rotation in extension (Degrees)**	
Side	Non operated	Operated	Non operated	Operated
	5	5	10	15
	40	20	10	20
	40	30	15	15
	45	55	15	10
	20	40	40	20
	30	35	40	45
	33	40	30	20
	20	15	12	25
	30	5	40	65
	15	20	22	28
	32	25	32	20
	40	25	25	20
	50	35	10	20
	42	22	30	38
	20	30	0	0
	23	22	20	15
	30	34	40	15
	35	50	40	25
	37	35	27	27
	60	55	25	5
	30	30	-5	5
	35	25	30	30
	33	25	10	12
	20	55	15	10
Mean	31.88	30.54	22.21	21.04
SD	11.99	13.93	13.18	13.87

THR Horizontal Plane data by operated side

	External Rotation (In 70° Flexion) (Degrees)		**Internal Rotation (In 70° Flexion) (Degrees)**	
Side	Non operated	Operated	Non operated	Operated
	25	10	5	10
	10	15	5	10
	10	10	5	5
	15	15	5	-5
	45	15	15	5
	30	40	10	5
	40	30	20	15
	10	5	-10	15
	45	15	15	50
	40	30	20	15
	30	10	10	15
	30	25	10	5
	40	29	10	25
	42	10	25	20
	5	-5	10	15
	40	20	10	5
	40	20	50	15
	25	25	40	40
	20	5	10	15
	40	40	30	30
	20	20	-5	0
	45	40	35	20
	40	25	10	20
	15	30	30	30
Mean	29.25	19.96	15.21	15.83
SD	13.24	11.85	13.95	12.57

d) Raw Data for Sagittal and Frontal plane movement when right and left data are considered together.

Sagittal Plane: n=48 per group				
	Flexion (°)		Extension (°)	
	THR	THN	THR	THN
Mean	99.38	115.79	0.48	12.67
SD	15.86	7.23	3.88	5.94
Min	60.00	100.00	-15.00	0.00
Max	125.00	130.00	10.00	22.00

Frontal plane: n=48 per group				
	Abduction (°)		Adduction (°)	
	THR	THN	THR	THN
Mean	30.25	33.44	24.10	29.83
SD	9.86	4.58	10.97	3.36
Min	10.00	27.00	0.00	21.00
Max	45.00	42.00	40.00	40.00

e) THR Group Hip range of motion by operated and non-operated side (non THR) Sagittal and Frontal plane motion

	Flexion (Degrees)		**Extension (Degrees)**		**Abduction (Degrees)**		**Adduction (Degrees)**	
	Non THR	THR	Non THR	THR	Non THR	THR	Non THR	THR
	120	120	-15	0	30	40	20	30
	107	105	0	0	30	25	10	10
	90	80	0	5	20	10	15	7
	90	87	0	0	20	15	10	10
	110	90	0	0	35	30	20	20
	110	105	0	0	40	30	0	0
	110	90	0	0	40	40	30	30
	65	60	0	0	15	15	15	15
	95	95	0	0	30	30	25	30
	120	110	0	0	40	40	30	30
	105	90	0	5	35	25	30	30
	115	100	0	0	35	35	30	30
	105	80	0	0	40	35	30	20
	108	100	0	0	45	30	30	30
	75	70	-5	-12	30	12	20	20
	105	100	0	0	35	30	20	20
	90	70	5	5	35	30	40	40
	110	115	0	0	30	30	40	40
	115	110	5	5	35	20	40	30
	120	110	0	0	40	30	30	30
	85	95	0	10	20	20	30	30
	125	120	0	0	30	30	40	40
	110	105	0	0	40	20	10	10
	110	115	10	7	35	40	25	30
Mean	103.96	96.75	0.00	1.04	32.71	27.58	24.58	24.25
SD	14.87	16.27	4.17	3.99	7.66	8.93	10.83	10.96

Non THR = The hip which was not operated on.

THR = The hip which had a Total Hip Replacement

THR Group Hip range of motion by operated and non-operated side (non THR)

(Continued) Transverse Plane motion

	External (ext.) (Degrees)		Internal (ext.) (Degrees)		External (70 flexion) (Deg.)		Internal (70 flexion) (Deg.)	
	Non THR	THR	Non THR	THR	Non THR	THR	Non THR	THR
	5	5	10	15	25	10	5	10
	40	20	10	20	10	15	5	10
	40	30	15	15	10	10	5	5
	45	55	15	10	15	15	5	-5
	20	40	40	20	45	15	15	5
	30	35	40	45	30	40	10	5
	33	40	30	20	40	30	20	15
	20	15	12	25	10	5	-10	15
	30	5	40	65	45	15	15	50
	15	20	22	28	40	30	20	15
	32	25	32	20	30	10	10	15
	40	25	25	20	30	25	10	5
	50	35	10	20	40	29	10	25
	42	22	30	38	42	10	25	20
	20	30	0	0	5	-5	10	15
	23	22	20	15	40	20	10	5
	30	34	40	15	40	20	50	15
	35	50	40	25	25	25	40	40
	37	35	27	27	20	5	10	15
	60	55	25	5	40	40	30	30
	30	30	-5	5	20	20	-5	0
	35	25	30	30	45	40	35	20
	33	25	10	12	40	25	10	20
	20	55	15	10	15	30	30	30
Mean	31.88	30.54	22.21	21.04	29.25	19.96	15.21	15.83
SD	11.99	13.93	13.18	13.87	13.24	11.85	13.95	12.57

Non THR = The hip which was not operated on.

THR = The hip which had a Total Hip Replacement

THR Group Hip range of motion by operated and non-operated side (non THR)

(Continued) Knee movement

	Knee Flexion (Degrees)		Knee Extension (Degrees)	
	Non THR	THR	Non THR	THR
	120	130	0	0
	100	100	0	0
	100	100	0	0
	130	130	5	7
	130	130	0	0
	140	140	0	0
	145	140	0	0
	135	130	0	0
	145	140	0	0
	135	133	0	0
	130	127	3	5
	140	140	0	0
	125	110	0	0
	135	135	0	0
	125	125	0	0
	130	140	0	0
	130	65	5	10
	130	135	5	0
	140	140	0	0
	110	135	2	0
	130	130	0	0
	130	132	0	0
	130	130	0	0
	100	107	3	0
Mean	127.71	126.00	0.96	0.92
SD	13.10	17.81	1.81	2.59

Non THR = The hip which was not operated on.

THR = The hip which had a Total Hip Replacement

2) Statistical Analysis

a) Repeated measures ANOVA between groups and sides

Flexion

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	6468.167	1	6468.167	37.291	.000
Error(GROUP)	3989.333	23	173.449		
Side	57.042	1	57.042	1.611	.217
Error(SIDE)	814.458	23	35.411		
Group * side	100.042	1	100.042	3.453	.076
Error(GROUP*SIDE)	666.458	23	28.976		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1111120.667	1	1111120.667	2953.799	.000
Error	8651.833	23	376.167		

Extension

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	3564.844	1	3564.844	109.996	.000
Error(GROUP)	745.406	23	32.409		
Side	3.010	1	3.010	.524	.477
Error(SIDE)	132.240	23	5.750		
Group * side	3.010	1	3.010	.508	.483
Error(GROUP*SIDE)	136.240	23	5.923		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	4147.510	1	4147.510	70.832	.000
Error	1346.740	23	58.554		

Abduction

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	243.844	1	243.844	3.264	0.084
Error(GROUP)	1718.406	23	74.713		
Side	1.260	1	1.260	.055	0.816
Error(SIDE)	523.990	23	22.782		
Group * side	2.344	1	2.344	.107	0.746
Error(GROUP*SIDE)	501.906	23	21.822		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	97346.344	1	97346.344	797.663	0.000
Error	2806.906	23	122.039		

Adduction

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	787.760	1	787.760	6.221	0.020
Error(GROUP)	2912.490	23	126.630		
Side	8.760	1	8.760	.852	0.366
Error(SIDE)	236.490	23	10.282		
Group * side	3.010	1	3.010	.386	0.540
Error(GROUP*SIDE)	179.240	23	7.793		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	69822.094	1	69822.094	563.248	.000
Error	2851.156	23	123.963		

External Rotation in Hip Extension

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	35458.594	1	35458.594	221.697	.000
Error(GROUP)	3678.656	23	159.942		
Side	44.010	1	44.010	2.342	.140
Error(SIDE)	432.240	23	18.793		
Group * side	21.094	1	21.094	.758	.393
Error(GROUP*SIDE)	640.156	23	27.833		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	233741.344	1	233741.344	1466.900	.000
Error	3664.906	23	159.344		

Internal Rotation in Hip Extension

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	21540.042	1	21540.042	83.800	.000
Error(GROUP)	5911.958	23	257.042		
Side	165.375	1	165.375	8.065	.009
Error(SIDE)	471.625	23	20.505		
Group * side	376.042	1	376.042	13.327	.001
Error(GROUP*SIDE)	648.958	23	28.216		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	125715.375	1	125715.375	686.052	.000
Error	4214.625	23	183.245		

External Rotation in 70° Hip Flexion

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	13968.375	1	13968.37	134.192	.000
Error(GROUP)	2394.125	23	104.09		
Side	70.042	1	70.04	1.099	.305
Error(SIDE)	1465.458	23	63.72		
Group * side	37.500	1	37.50	.531	.474
Error(GROUP*SIDE)	1624.000	23	70.61		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	136504.167	1	136504.167	543.527	.000
Error	5776.333	23	251.145		

Internal Rotation in 70° Hip Flexion

Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	8475.042	1	8475.04	57.79	.000
Error(GROUP)	3372.458	23	146.63		
Side	273.375	1	273.37	8.57	.008
Error(SIDE)	734.125	23	31.92		
Group * side	368.167	1	368.17	12.84	.002
Error(GROUP*SIDE)	659.333	23	28.67		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	54721.500	1	54721.500	341.453	.000
Error	3686.000	23	160.261		

b) Statistical comparison of hip range between THR and THN groups

Independent Samples Test

	t-test for Equality of Means						
	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	Equal variances assumed					Lower	Upper
Flexion	-6.53	94	0.000	-16.42	2.52	-21.42	-11.42
Extension	-11.90	94	0.000	-12.19	1.02	-14.22	-10.15
Abduction	-2.03	94	0.045	-3.19	1.57	-6.30	-0.07
Adduction	-3.46	94	0.001	-5.73	1.66	-9.02	-2.44
External Rotation in Extension	-20.66	94	0.000	-39.19	0.90	-42.95	-35.42
Internal Rotation in Extension	-13.11	94	0.000	-29.96	2.29	-34.50	-25.42
External Rotation in 70° Flexion	-10.75	94	0.000	-24.13	2.25	-28.58	-19.67
Internal Rotation in 70° Flexion	-9.36	94	0.000	-18.79	2.01	-22.78	-14.81

c) Statistical comparison of hip range between right and left sides per classification

Paired Samples Ttest

THR	Paired Differences					t	df	Sig. (2-tailed)
	Mean	SD	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Flexion	-3.58	11.15	2.28	-8.29	1.13	-1.57	23	0.129
Extension	0.71	4.36	.89	-1.13	2.55	.80	23	0.434
Abduction	-0.083	9.03	1.84	-3.90	3.73	-.05	23	0.964
Adduction	-.96	5.77	1.18	-3.40	1.48	-.81	23	0.425
External Rot in Extension	0.42	9.40	1.92	-3.55	4.38	.22	23	0.83
Internal Rot in Extension	-6.58	9.67	1.97	-10.67	-2.50	-3.33	23	0.003
External Rot in 70°Flexion	-2.96	16.33	3.33	-9.85	3.94	-.89	23	0.384
Internal Rot in 70°F	-7.29	10.93	2.23	-11.91	-2.68	-3.27	23	0.003

THN	Paired Differences					t	df	Sig. (2-tailed)
	Mean	SD	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Flexion	0.50	2.11	.43	-.39	1.39	1.16	23	0.257
Extension	0.00	2.08	.43	-.88	.88	.00	23	1.0
Abduction	0.54	2.78	.57	-.63	1.72	.95	23	0.350
Adduction	-0.25	1.67	.34	-.96	.46	-.73	23	0.472
External Rot in Extension	0.63	2.32	0.47	-0.35	1.60	1.32	23	0.200
Internal Rot in Extension	1.33	1.97	0.40	0.50	2.17	3.31	23	0.003
External Rot in 70°Flexion	-0.46	1.38	0.28	-1.04	0.13	-1.62	23	0.118
Internal Rot in 70°Flexion	0.54	1.29	0.26	-0.0008	1.08	2.07	23	0.050

Appendix P: Passive Physiological Lumbar Spine Movement

1) Raw Data

a) Sagittal Plane Movement: Flexion & Extension Measured in Degrees

	Flexion		Extension	
	THR	THN	THR	THN
	28	-74	-7	-16
	45	-34	-12	-19
	38	-50	-7	-21
	22	-29	2	3
	13	-50	-8	-7
	27	-39	-10	-11
	34	-70	-16	21
	46	-57	-12	-1
	42	-39	-11	0
	62	-60	-7	5
	5	-27	-11	-10
	40	-56	0	-9
	50	-56	-7	17
	18	-57	-12	4
	45	-38	-25	-8
	17	-45	-11	15
	12	-40	-10	-5
	38	-32	-6	10
	35	-45	-8	-10
	28	-51	-4	16
	38	-72	-12	-14
	10	-65	-23	-8
	28	-63	-5	18
	53	-40	-12	-13
	18	-32	-12	-16
Mean	31.68	48.81	-9.84	-2.31
SD	14.78	13.81	5.85	12.63

b) Frontal Plane Movement: Lateral Lumbar Flexion Measured in Centimetres

	THR		THN	
	Right	Left	Right	Left
	13	10.1	11.5	11
	13	17.4	19	18
	12	13.8	18.5	15
	14.5	15.6	17	16.5
	9.2	8.4	19.5	21.5
	14	9.5	16	17
	15	13.5	21.5	22
	13	12.5	14	14
	14	16	14	13
	17.5	18	16	16
	13	12	15.5	15.5
	10.5	10	15	13
	13	12.5	18.5	16.4
	8.5	9.5	14	13.5
	16.5	16.5	14.3	14.5
	10	12	11.5	11
	8	9	14	13
	15	17	16.5	17
	13.5	13.5	18	17.5
	12.8	13	16	16.5
	19	19.5	17	17
	13.5	10.5	21	21
	13.5	13.5	16	16
	11	10	13	12
	6	4	11.5	11
Mean	12.76	12.69	16.06	15.62
SD	2.95	3.58	2.74	3.00

c) Lumbar Spine Static Posture: Measured in Degrees
Kyphosis (+) or Lordosis (-)

THR	THN
Mean (°)	Mean (°)
-5	-34
-42.5	-28
-35	-39
-42	-21.5
-22.5	-30
-24	-26.5
-66	-44
-38.5	-43
-31.5	-42
-37.5	-37.5
-26.5	-21
-25	-21
-27.5	-39.5
-35.5	-33
-19	-49
-19	-45.5
-11	-32
-23	-34
-30.5	-45
-42.5	-32
-28	-21
-10	-20
-17.5	-38
-43.5	-45
-23	-45
-29.04	-34.66
13.10	9.19

Key: Mean = Static posture measurement prior to lumbar spine flexion – that prior to extension

2) Statistical Analysis

a) Sagittal Plane Movement

Independent Samples Test: Equal variances assumed

Lumbar extension (Degrees)

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
0.754	46	0.455	2.25	2.99	-3.76	8.26

Independent Samples Test: Equal variances assumed

Lumbar Spine Flexion (Degrees)

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
3.879	46	.000	16.25	4.19	7.82	24.68

b) Frontal Plane Movement

Independent Samples Test: Equal variances assumed
Lateral Lumbar Flexion (cm)

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
-5.336	94	.000	-3.23	.61	-4.44	-2.03

Paired Samples Test Comparison of right to left side flexion in each group

	Paired Differences					t	df	Sig. (2 tailed)
	Mean	SD	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
THR	0.05	1.93	0.39	-0.76	0.86	0.127	23	0.90
THN	0.26	1.23	0.25	-0.26	0.78	1.030	23	0.31

c) Lumbar Spine Static posture

Independent Samples Test: Equal variances assumed

Static Lumbar Spine Posture comparison between groups

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
2.167	46	0.035	7.27	3.36	0.52	14.03

Appendix Q: Passive Physiological Knee movement

a) Raw data – by side

	Extension (°)				Flexion (°)			
	THR		THN		THR		THN	
	Right	Left	Right	Left	Right	Left	Right	Left
	0	0	0	3	120	130	121	125
	0	0	0	0	100	100	134	135
	0	0	0	0	100	100	129	130
	7	5	0	0	130	130	135	131
	0	0	0	0	130	130	130	125
	0	0	0	0	140	140	134	134
	0	0	5	5	140	145	130	129
	0	0	0	0	135	130	126	126
	0	0	0	0	145	140	134	136
	0	0	0	0	133	135	140	140
	5	3	0	0	127	130	135	136
	0	0	0	0	140	140	131	130
	0	0	5	5	125	110	140	141
	0	0	3	0	135	135	137	138
	0	0	3	0	125	125	140	141
	0	0	0	0	140	130	138	135
	10	5	0	0	65	130	136	138
	0	5	3	0	135	130	135	134
	0	0	0	0	140	140	137	137
	0	2	0	0	135	110	129	130
	0	0	0	5	130	130	141	140
	0	0	0	3	132	130	139	135
	0	0	4	3	130	130	143	140
	3	0	0	0	100	107	129	127
Mean	1.04	0.83	0.96	1.00	126.33	127.38	134.29	133.88
SD	2.61	1.76	1.76	1.84	18.18	12.62	5.32	5.17

b) Raw data – by operated side

	Extension (°)		Flexion (°)	
	Operated	Non - Operated	Operated	Non – Operated
	0	0	130	120
	0	0	100	100
	0	0	100	100
	7	5	130	130
	0	0	130	130
	0	0	140	140
	0	0	140	145
	0	0	130	135
	0	0	140	145
	0	0	133	135
	5	3	127	130
	0	0	140	140
	0	0	110	125
	0	0	135	135
	0	0	125	125
	0	0	140	130
	5	5	130	130
	0	5	135	130
	0	0	140	140
	0	2	135	110
	0	0	130	130
	0	0	132	130
	0	0	130	130
	0	3	107	100
Mean	0.71	0.96	128.71	127.71
SD	1.94	1.81	12.18	13.10

c) Statistical Analysis

Knee Flexion
Tests of Within-Subjects Contrasts:

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	1254.26	1	1254.26	6.29	0.02
Error(GROUP)	4582.99	23	199.26		
Side	2.34	1	2.34	0.04	0.85
Error(SIDE)	1459.91	23	63.47		
Group * side	12.76	1	12.76	0.23	0.64
Error(GROUP*SIDE)	1302.49	23	56.63		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1634121.09	1	1634121.09	7251.33	0.000
Error	5183.16	23	225.36		

Knee Extension
Tests of Within-Subjects Contrasts

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	4.167E-02	1	4.167E-02	.005	0.94
Error(GROUP)	189.96	23	8.259		
Side	0.17	1	0.167	.138	0.71
Error(SIDE)	27.83	23	1.210		
Group * side	0.375	1	0.375	.202	0.66
Error(GROUP*SIDE)	42.63	23	1.853		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	88.17	1	88.17	17.36	0.000
Error	116.83	23	5.08		

Comparison between groups all data

Independent Samples Test: Equal variances assumed

Knee Flexion

t-test for Equality of Means						
t	Df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
-3.066	94	0.003	-7.23	2.36	-11.91	-2.55

Knee Extension

t-test for Equality of Means						
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	Upper
-.102	94	0.919	-0.04	0.41	-0.85	0.77

Paired t-test for comparison of knee movement between operated and non-operated knee

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	SD	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Extension	0.25	1.39	0.28	-0.34	0.84	0.88	23	0.39
Flexion	-1.00	7.20	1.47	-4.04	2.04	-0.68	23	0.50

Paired t-test for comparison of knee movement between right and left sides by classification

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	SD	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Extension								
THR	0.21	1.74	0.36	-0.53	0.94	0.59	23	0.56
THN	-0.04	1.76	0.36	-0.78	0.70	-0.12	23	0.91
Flexion								
THR	-1.04	15.34	3.13	-7.52	5.44	-0.33	23	0.74
THN	0.42	2.19	0.45	-0.51	1.34	0.93	23	0.36

Appendix R: Biomechanical Hip movement

1) Raw Data (n = 24 per group (THR and THN)

a) Range of motion from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN
	36.97	32.43	33.20	10.88	7.18	13.46	14.38	8.29	6.52
	31.70	29.08	32.31	5.74	6.15	8.37	4.73	7.66	3.90
	21.60	35.93	42.00	3.55	5.13	12.48	6.15	4.69	11.82
	27.72	28.42	37.05	7.19	7.83	9.16	10.88	5.55	6.11
	21.88	34.53	43.32	2.51	7.92	12.55	5.91	4.79	12.07
	24.35	40.32	51.40	5.10	8.89	15.26	8.33	8.02	8.55
	31.27	39.51	43.60	11.33	11.93	9.58	7.19	5.75	13.98
	23.99	26.28	44.73	4.27	3.97	12.53	6.22	4.60	8.14
	10.13	24.21	51.83	13.91	4.48	9.27	7.19	4.97	9.86
	32.60	48.69	44.47	8.66	12.82	11.81	6.95	6.61	10.75
	33.35	22.56	46.13	5.98	7.19	29.46	6.42	6.15	11.92
	19.77	46.25	39.59	6.07	9.06	8.96	3.99	4.68	3.31
	25.31	48.14	44.69	10.29	9.16	13.59	16.41	8.88	10.50
	36.48	48.06	39.26	9.73	9.54	5.26	13.05	9.90	6.09
	31.26	41.40	33.20	6.85	9.85	13.46	4.61	10.30	6.52
	19.19	27.17	43.32	4.29	8.96	12.55	4.29	5.90	12.07
	19.14	36.73	47.11	5.84	4.07	8.04	6.39	5.69	17.57
	44.43	50.25	44.36	8.53	8.70	11.59	6.71	7.31	7.48
	31.81	48.03	47.11	8.07	11.21	8.04	7.24	6.30	17.57
	33.34	28.44	37.05	8.81	4.57	9.16	7.06	5.06	6.11
	35.95	27.29	42.69	10.42	9.16	10.60	5.58	6.51	11.57
	35.44	27.92	47.36	11.23	10.96	11.46	5.93	6.95	9.75
	34.19	34.82	36.35	8.15	6.52	9.47	5.40	7.08	5.16
	34.16	45.06	42.00	10.55	10.02	12.48	7.57	9.31	11.82
Mean	29.00	36.31	42.25	7.83	8.14	11.61	7.44	6.71	9.55
SD	7.74	8.99	5.35	2.89	2.50	4.46	3.15	3.70	3.81

b) Hip position at Heel Strike from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN
	19.66	26.51	30.67	12.11	-4.78	9.47	10.67	-2.20	-8.83
	33.22	26.12	17.05	5.57	-4.58	19.66	26.51	30.67	12.11
	23.10	23.48	34.89	12.34	8.31	1.25	-5.54	-5.11	7.71
	27.94	33.00	19.24	3.83	19.09	12.95	-15.69	-5.61	-12.38
	20.53	30.18	33.83	10.10	7.86	4.51	-5.30	2.72	-2.01
	17.90	39.35	40.49	13.43	7.58	8.31	-8.06	-4.30	-9.93
	25.31	20.94	28.09	10.69	13.33	8.23	-4.62	-3.48	-10.44
	28.02	28.67	22.01	10.36	3.57	14.19	6.97	-9.69	-8.80
	16.61	28.40	33.55	-2.21	4.53	10.49	-4.62	-12.14	-9.90
	34.32	29.47	30.24	8.03	5.74	7.66	0.27	0.25	-10.12
	33.82	30.00	31.21	6.87	15.81	2.82	-0.65	2.09	-6.46
	13.06	36.75	29.95	15.75	-1.53	6.46	-11.75	-13.91	-7.74
	32.71	33.89	22.43	4.89	15.15	12.61	6.53	-2.67	-0.11
	15.92	32.62	21.46	12.02	14.19	8.34	5.11	-2.22	-8.37
	30.59	19.40	30.67	1.83	10.53	9.47	-6.70	2.01	-8.83
	14.54	23.49	33.83	16.97	-2.99	4.51	-11.06	12.49	-2.01
	16.77	27.87	33.61	18.20	6.17	1.62	-15.44	-8.10	-0.91
	23.20	31.56	26.60	11.05	15.86	5.50	4.18	-4.24	-1.67
	30.27	38.00	33.61	4.27	-1.81	1.62	6.52	-13.40	-0.91
	29.96	29.84	29.24	9.78	2.58	12.95	8.75	-8.66	-12.38
	34.90	23.82	36.34	10.35	-2.40	1.35	4.87	13.73	-8.30
	19.18	22.62	36.34	14.70	-4.60	1.35	-3.46	12.16	-8.30
	34.26	27.06	28.64	12.95	4.35	4.38	3.76	-12.26	-7.72
	34.93	34.12	34.89	12.74	4.11	1.25	6.88	1.21	7.71
Mean	25.45	29.05	29.95	9.86	5.67	6.46	-1.34	-2.61	-5.86
SD	7.47	5.29	5.91	4.94	7.33	4.25	7.78	7.74	5.61

c) Hip position at Toe off from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Non Op	THR Op	THN
	-0.28	6.77	6.69	1.23	-4.43	-0.09	-5.41	-5.09	-10.31
	12.88	4.28	2.7	3.24	-4.78	-1.73	-8.06	-5.38	-10.01
	9.98	7.08	8.48	9.59	4.87	-4.72	-13.6	-11.77	12.32
	21.84	12.90	-5.79	5.45	14	4.42	-9.02	-1.59	-14.02
	1.59	7.31	-3.08	9.49	3.56	1.76	-12.03	-2.96	-13.53
	3.3	17.46	3.34	9.94	6.78	8.19	-12.27	-8.42	-2.09
	10.78	-4.64	-5.14	6.24	6.05	3.2	-9.09	-3.15	-10.57
	13.58	12.86	-7.71	8.17	3.97	9.82	1.28	-10.49	-13.84
	9.18	15.13	-10.45	3.34	3.89	6.57	-4.72	-11.79	-7.71
	5.59	-15.06	-9.08	4.13	2.41	9.04	-3.04	-3.12	-13.48
	22.03	23.45	3.8	7.32	10.63	5.52	-0.86	-4.57	-11.9
	15.4	2.68	-3.89	16.39	0.94	4.05	-13.67	-14.29	-11.23
	11.97	-1.81	10.32	-2.96	11.89	6.74	-7.12	-10.47	-16.01
	1.85	2.55	-3.65	6.05	11.59	10.42	-3.54	-9.76	-10.52
	8.89	-6.00	11.28	1.72	6.64	-0.09	-8.6	2.4	-10.31
	11.35	2.38	-6.04	16.33	-3.82	2.77	-14.36	3.73	-11.47
	12.4	1.77	-9.56	16.39	3.28	3.81	-14.58	-10.84	-8.23
	-4.50	-3.96	2.72	5.13	12.28	1.61	-9.24	-8.68	-12.92
	5.92	-4.84	-2.42	3.14	6.17	1.04	2.37	-3.78	-8.48
	9.29	11.30	4.21	3.99	4.15	4.42	2.05	-8.25	-14.02
	9.87	1.26	1.49	5.8	-3.66	-3.16	-0.94	4.22	-18.97
	-5.93	0.22	2.94	8.59	-4.75	-2.97	-6.67	0.04	-14.02
	16.6	6.33	-7.55	8.95	0.91	3.65	-1.94	-10.74	-14
	25.84	-5.97	1.03	9.35	13.44	-4.3	9.35	-9.61	18.87
Mean	9.56	3.89	-0.64	6.96	4.42	2.92	-5.99	-6.02	-9.44
SD	7.88	8.78	6.43	4.79	5.93	4.37	6.21	5.22	8.43

d) Mean Sagittal plane motion through the Gait Cycle (°) (n=24)

% Time	THR OP	THR NON OP	THN
0	25.45	29.05	29.95
2	24.92	28.79	29.72
4	24.38	28.68	29.55
6	23.93	28.47	28.54
8	22.88	27.81	27.58
10	21.30	26.49	26.02
12	19.98	24.69	24.05
14	18.81	22.91	22.15
16	17.86	21.38	20.24
18	16.87	19.98	18.19
20	15.86	18.39	16.11
22	14.74	16.68	13.89
24	13.54	14.85	11.64
26	12.34	12.87	9.45
28	11.15	10.96	7.38
30	10.00	9.20	5.38
32	8.99	7.61	3.46
34	8.21	6.09	1.68
36	7.29	4.67	-0.10
38	6.41	3.32	-1.72
40	5.56	2.00	-3.30
42	4.51	0.71	-4.65
44	3.83	-0.40	-6.31
46	3.07	-1.52	-7.57
48	2.30	-2.51	-8.55
50	1.53	-3.27	-9.31
52	0.96	-3.49	-9.64
54	1.05	-3.41	-9.20
56	1.63	-2.78	-8.20
58	2.86	-1.60	-6.48
60	4.62	0.24	-3.89
62	6.87	2.87	-0.75
64	9.56	5.79	2.61
66	12.25	8.89	6.38
68	14.86	12.00	9.84
70	17.43	15.21	13.28
72	19.83	18.33	16.68
74	21.85	21.38	19.47
76	23.59	24.17	22.30
78	25.31	26.39	24.82
80	26.66	28.28	26.73
82	27.47	29.89	28.31
84	28.00	30.86	29.09
86	28.22	31.35	29.53
88	28.21	31.31	29.81
90	27.93	30.78	29.74
92	27.62	30.09	29.47
94	27.50	29.44	29.21
96	27.32	29.20	29.51
98	26.92	28.84	29.42
100	25.91	28.53	28.59

e) Mean Frontal plane motion through the Gait Cycle (°) (n=24)

% Time	THR OP	THR NON OP	THN
0	2.86	-1.33	-0.54
2	2.84	-1.01	-0.06
4	3.22	-0.43	0.81
6	3.77	0.26	2.07
8	4.08	1.00	2.94
10	4.11	1.63	3.57
12	3.97	2.03	4.00
14	4.04	2.18	4.23
16	4.21	2.18	4.26
18	4.29	2.13	4.14
20	4.29	2.17	4.04
22	4.21	2.15	3.89
24	4.19	2.09	3.83
26	4.10	1.94	3.73
28	3.91	1.77	3.66
30	3.69	1.69	3.54
32	3.53	1.56	3.46
34	3.45	1.40	3.45
36	3.41	1.23	3.60
38	3.43	1.12	3.74
40	3.42	1.08	3.95
42	3.41	1.02	4.06
44	3.47	0.94	4.15
46	3.40	0.87	4.18
48	3.33	0.83	3.92
50	3.14	0.64	3.44
52	2.71	0.30	2.86
54	2.21	-0.18	1.87
56	1.57	-0.90	0.37
58	0.86	-1.81	-1.40
60	0.26	-2.61	-2.95
62	-0.09	-3.11	-4.01
64	-0.19	-3.22	-4.60
66	-0.12	-3.18	-4.69
68	0.08	-2.94	-4.48
70	0.40	-2.58	-4.16
72	0.80	-2.11	-3.78
74	1.35	-1.58	-3.38
76	2.05	-1.04	-2.86
78	2.56	-0.57	-2.34
80	2.96	-0.17	-1.77
82	3.27	0.36	-1.33
84	3.53	0.78	-1.06
86	3.69	0.86	-0.83
88	3.62	0.90	-0.67
90	3.42	0.65	-0.79
92	3.57	0.32	-1.22
94	3.54	0.13	-1.31
96	3.49	-0.09	-1.47
98	3.58	-0.16	-1.84
100	3.73	-0.04	-2.32

f) Mean Horizontal plane motion through the Gait Cycle (°) (n=24)

% Time	THR OP	THR NON OP	THN
0	-1.34	-2.61	-5.86
2	-2.86	-3.30	-5.87
4	-3.81	-3.92	-6.17
6	-4.36	-4.66	-6.48
8	-4.72	-5.20	-6.97
10	-4.91	-5.94	-7.56
12	-5.69	-6.95	-7.83
14	-6.47	-7.56	-7.96
16	-6.84	-8.23	-8.00
18	-6.73	-8.53	-8.06
20	-6.71	-9.10	-7.96
22	-6.76	-9.26	-7.97
24	-7.07	-9.30	-7.92
26	-7.09	-8.96	-7.76
28	-6.73	-8.35	-7.54
30	-6.39	-8.06	-7.26
32	-6.16	-7.52	-7.05
34	-6.10	-7.08	-6.92
36	-6.09	-6.87	-6.72
38	-6.00	-6.61	-6.45
40	-5.95	-6.33	-6.43
42	-5.91	-6.12	-6.21
44	-6.17	-6.53	-6.51
46	-6.43	-6.79	-6.88
48	-6.65	-6.89	-7.49
50	-6.83	-7.32	-8.01
52	-6.50	-7.85	-8.38
54	-6.60	-8.11	-8.51
56	-6.59	-7.99	-8.88
58	-6.43	-7.54	-9.18
60	-6.44	-7.17	-9.35
62	-6.69	-7.11	-9.88
64	-6.99	-7.25	-10.40
66	-7.13	-6.81	-10.71
68	-6.79	-6.13	-10.62
70	-6.10	-5.26	-10.47
72	-5.55	-4.20	-10.32
74	-4.83	-3.39	-9.86
76	-3.84	-2.59	-9.42
78	-2.75	-2.10	-9.14
80	-2.31	-2.34	-8.70
82	-1.81	-2.33	-7.60
84	-1.04	-2.11	-6.75
86	-0.84	-2.46	-5.96
88	-0.74	-2.56	-5.30
90	-0.38	-2.81	-4.39
92	-0.26	-3.28	-4.29
94	-0.29	-3.70	-3.89
96	-0.62	-3.98	-4.09
98	-0.53	-3.93	-4.23
100	0.23	-3.88	-5.55

g) Mean THN hip planar motion through the Gait Cycle (°) (n=24)

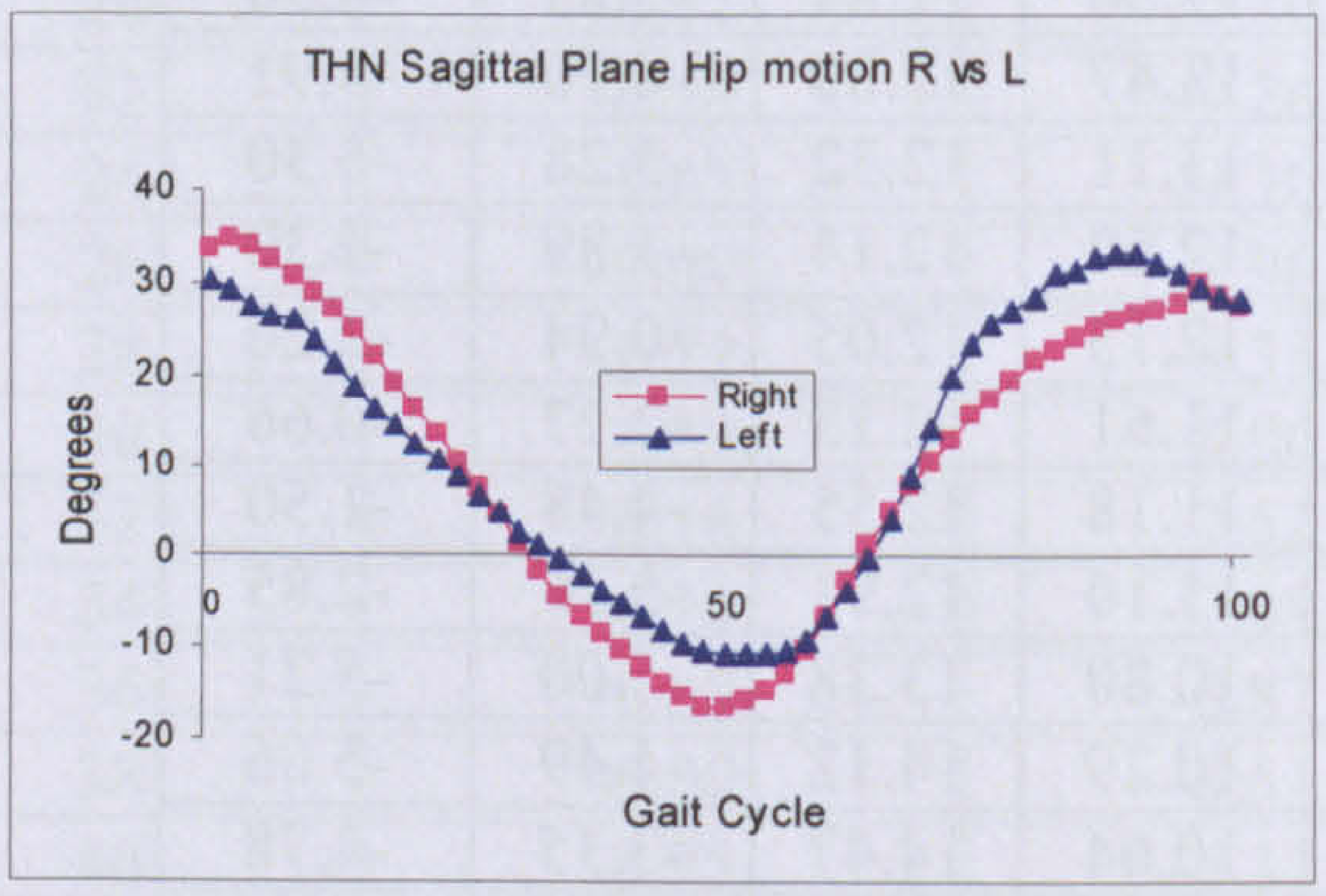
	Sagittal Plane		Frontal Plane		Horizontal Plane	
	Right	Left	Right	Left	Right	Left
0	33.55	30.24	10.49	7.66	-0.91	-1.67
2	34.62	29.28	11.57	8.50	-3.94	0.56
4	33.96	27.44	12.56	9.67	-6.06	0.88
6	32.33	26.50	13.18	10.80	-6.78	-0.67
8	30.63	25.95	13.62	11.66	-7.50	-4.06
10	28.85	23.96	13.96	12.01	-7.91	-6.32
12	26.97	21.23	14.28	12.33	-7.73	-7.02
14	24.80	18.64	14.51	12.81	-6.96	-5.56
16	22.00	16.44	14.26	13.09	-6.41	-4.90
18	19.06	14.47	13.74	13.13	-6.30	-4.40
20	16.35	12.47	13.50	12.88	-5.83	-4.50
22	13.30	10.55	13.47	12.80	-4.70	-5.91
24	10.32	8.64	13.11	12.52	-3.28	-5.30
26	7.41	6.68	12.60	12.14	-1.89	-4.30
28	4.43	4.71	12.15	12.05	-0.94	-2.20
30	1.30	2.69	11.61	12.13	-2.27	-0.66
32	-1.75	1.16	11.18	12.55	-4.48	-1.50
34	-4.45	-0.23	11.10	12.91	-5.16	-2.85
36	-6.85	-2.00	10.80	13.38	-5.00	-5.21
38	-8.68	-3.69	10.29	14.12	-4.49	-5.06
40	-10.47	-5.32	10.64	14.47	-3.35	-4.78
42	-12.26	-6.65	11.39	14.57	-3.61	-4.27
44	-13.93	-8.32	11.77	15.19	-5.40	-3.83
46	-15.49	-9.71	12.06	15.65	-7.27	-3.39
48	-16.39	-10.13	12.24	15.79	-9.17	-3.16
50	-16.27	-10.53	12.07	15.40	-10.07	-3.74
52	-15.54	-10.78	11.52	14.73	-9.94	-5.09
54	-14.54	-10.60	10.68	14.26	-9.61	-6.98
56	-12.99	-10.37	9.44	12.93	-9.36	-8.50
58	-10.45	-9.08	7.75	10.98	-8.98	-10.18
60	-6.69	-6.82	6.57	9.04	-8.23	-11.80
62	-2.73	-3.76	6.04	6.99	-8.02	-13.08
64	1.24	-0.13	5.55	5.48	-8.48	-13.35
66	4.71	3.94	5.23	4.44	-9.36	-12.92
68	7.69	8.63	5.38	3.98	-10.32	-12.38
70	10.28	14.08	5.86	3.99	-10.71	-12.19
72	12.78	19.73	6.18	4.73	-10.78	-11.13
74	15.45	23.50	6.20	5.57	-11.32	-9.53
76	17.48	25.49	6.54	6.47	-11.68	-8.14
78	19.64	27.03	7.17	7.21	-11.20	-6.97
80	21.57	28.59	7.45	8.13	-10.30	-6.39
82	22.74	31.02	7.78	8.58	-8.80	-6.46
84	24.26	31.50	8.21	8.80	-7.95	-7.72
86	25.36	32.70	8.78	8.90	-6.30	-8.55
88	26.12	33.19	9.35	8.90	-5.50	-7.14
90	26.62	33.10	9.67	9.29	-6.30	-7.72
92	27.12	32.00	9.65	9.20	-5.80	-8.50
94	27.93	30.93	9.47	8.90	-4.20	-8.40
96	29.79	29.58	9.47	8.90	-1.40	-7.70
98	28.50	28.65	9.63	8.90	0.60	-5.00
100	27.30	28.22	9.54	8.70	0.80	-2.20

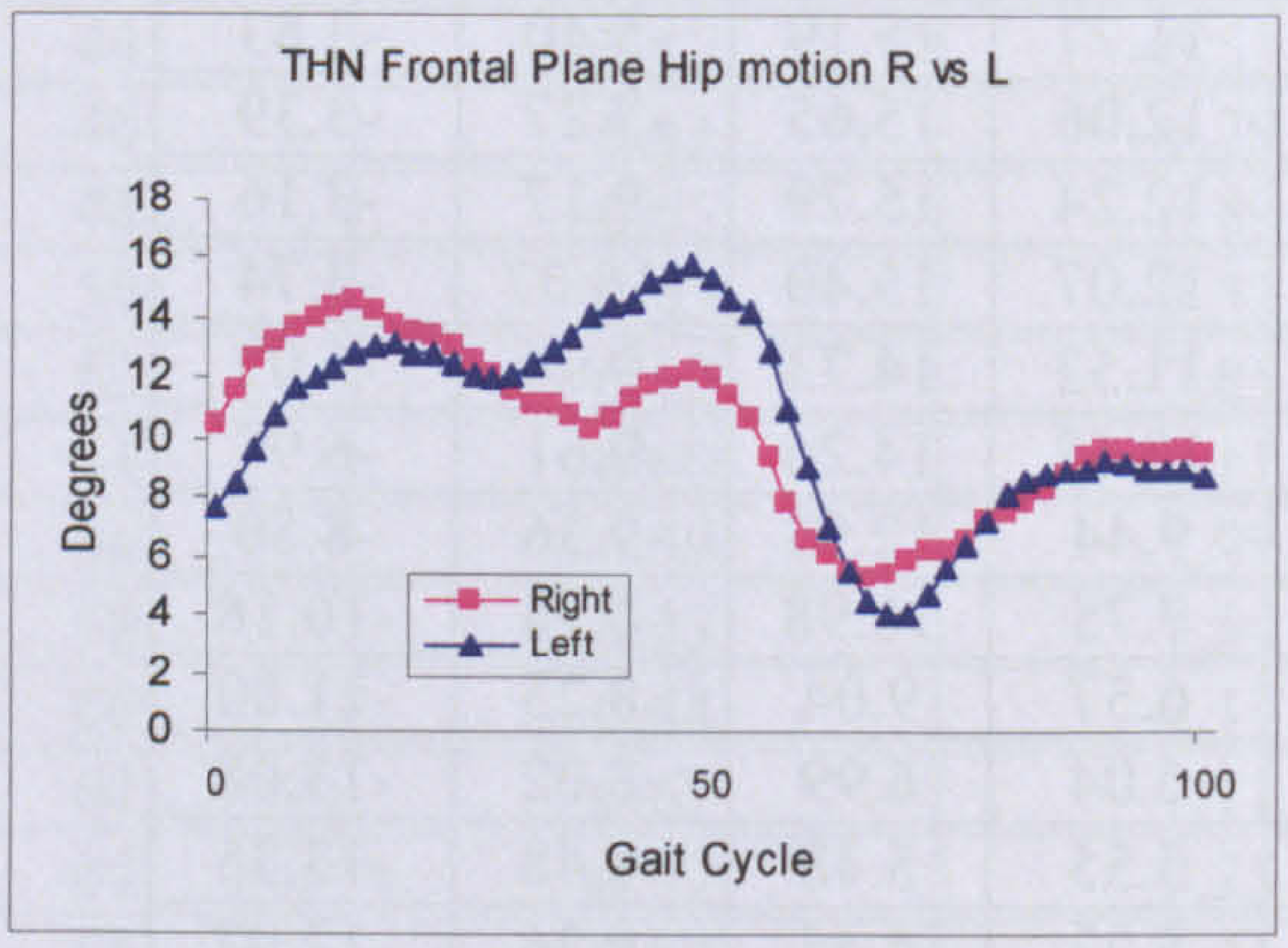
Hip movement, comparison of left and right sided data during walking

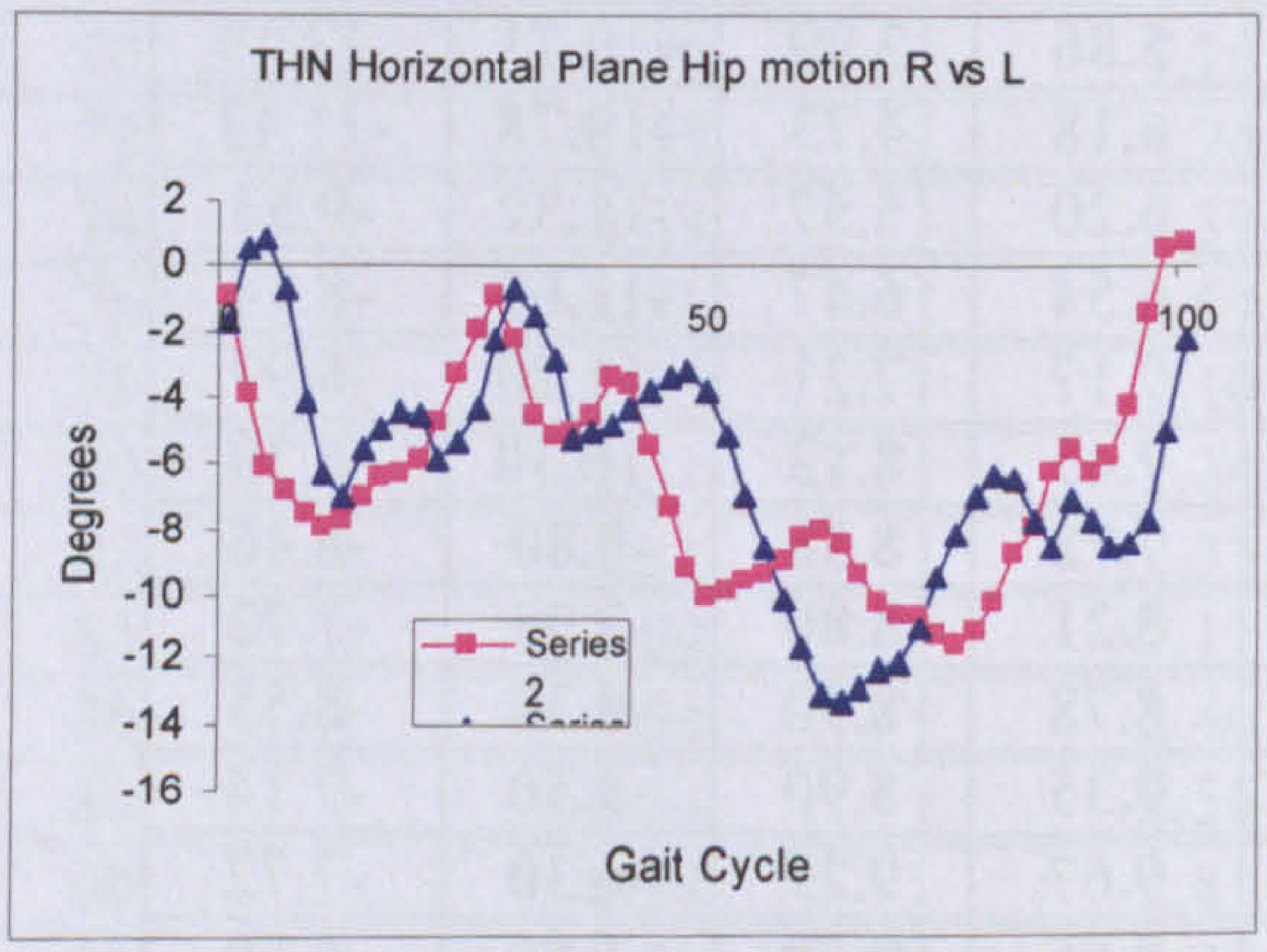
Two sample t-test between THN right and left data sets

	t value	p value
Sagittal	-0.53	0.59
Frontal	-0.56	0.58
Horizontal	-0.55	0.59

No significant difference between right and left data sets for hip data for each plane, tested by two sample t-test, significance set at $p \leq 0.05$







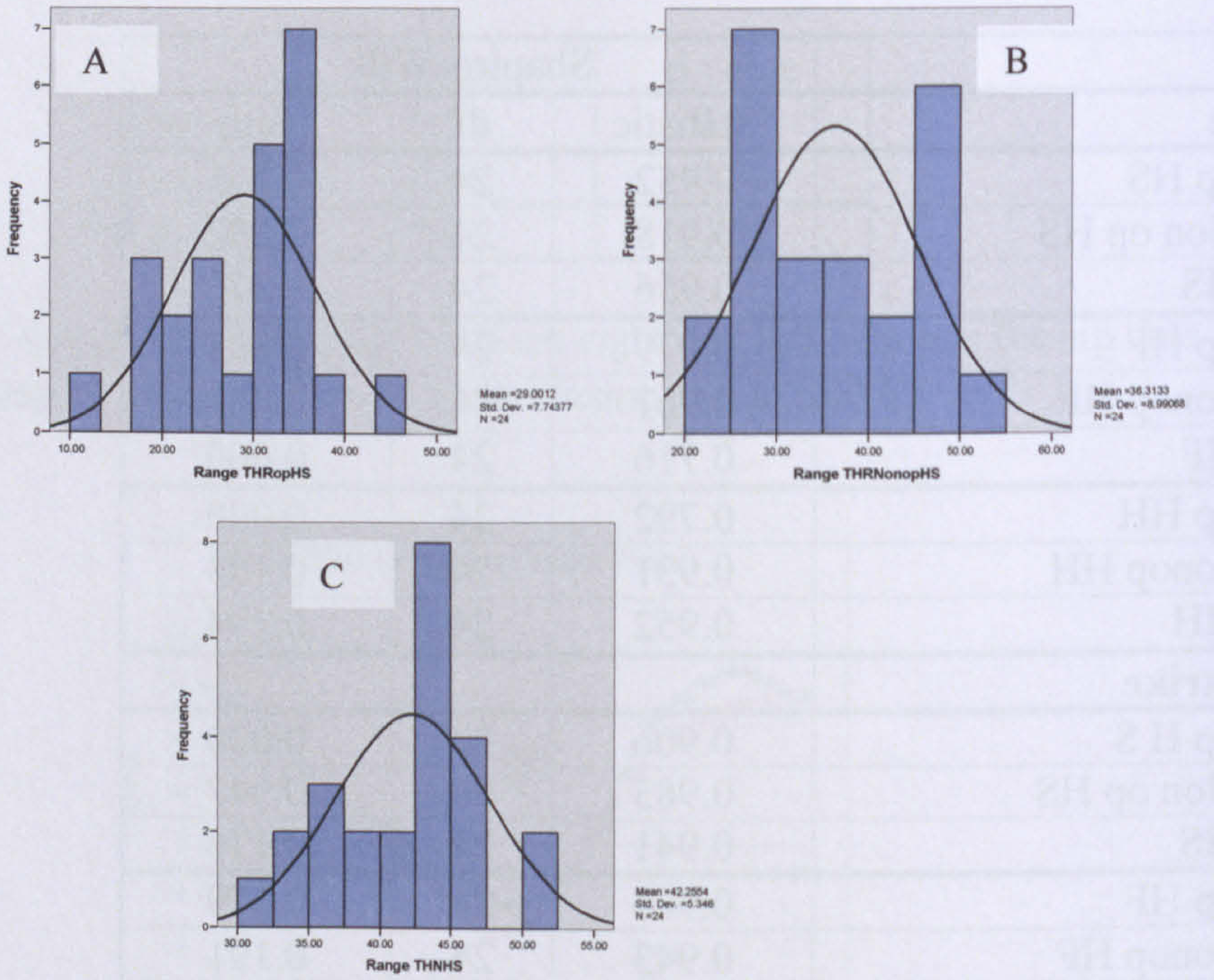
2) Test for Normal Distribution

a) **Tests of Normality** – Hip range of motion

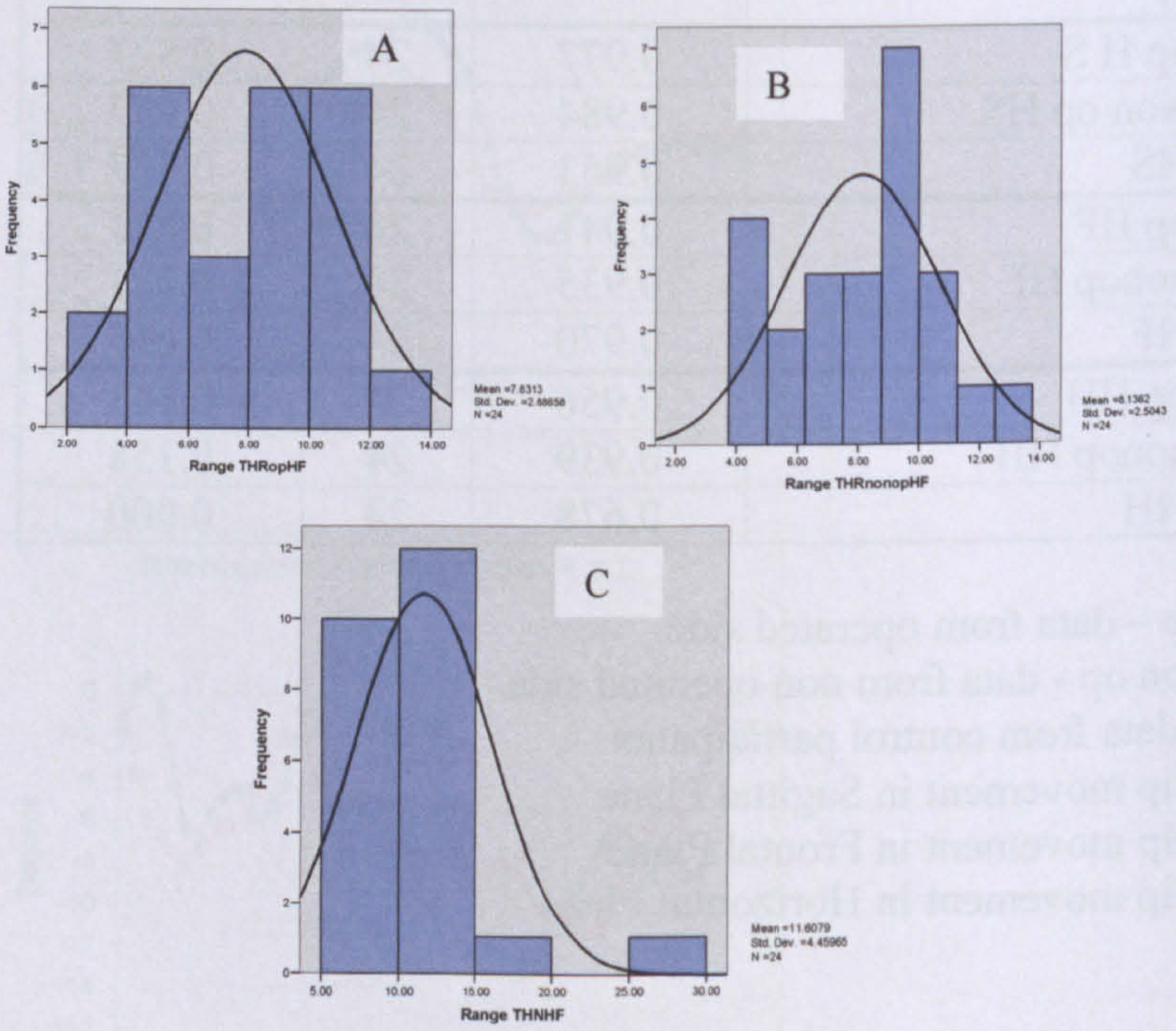
	Shapiro-Wilk		
Range	Statistic	df	Sig.
THR op HS	0.952	24	0.295
THR Non op HS	0.918	24	0.052
THN HS	0.956	24	0.370
THR op HF	0.979	24	0.868
THR nonop HF	0.961	24	0.462
THN HF	0.716	24	0.000
THR op HH	0.792	24	0.000
THR nonop HH	0.931	24	0.103
THN HH	0.952	24	0.294
Heel Strike			
THR op H S	0.906	24	0.030
THR Non op HS	0.983	24	0.947
THN HS	0.941	24	0.176
THR op HF	0.966	24	0.579
THR nonop HF	0.943	24	0.191
THN HF	0.918	24	0.053
THR op HH	0.943	24	0.192
THR nonop HH	0.934	24	0.117
THN HH	0.843	24	0.002
Toe off			
THR op H S	0.977	24	0.827
THR Non op HS	0.984	24	0.957
THN HS	0.953	24	0.317
THR op HF	0.941	24	0.173
THR nonop HF	0.935	24	0.123
THN HF	0.970	24	0.666
THR op HH	0.956	24	0.363
THR nonop HH	0.939	24	0.158
THN HH	0.678	24	0.000

THR op – data from operated side
THR non op - data from non operated side
THN - data from control participants
HS – Hip movement in Sagittal Plane
HF – Hip movement in Frontal Plane
HH - Hip movement in Horizontal Plane

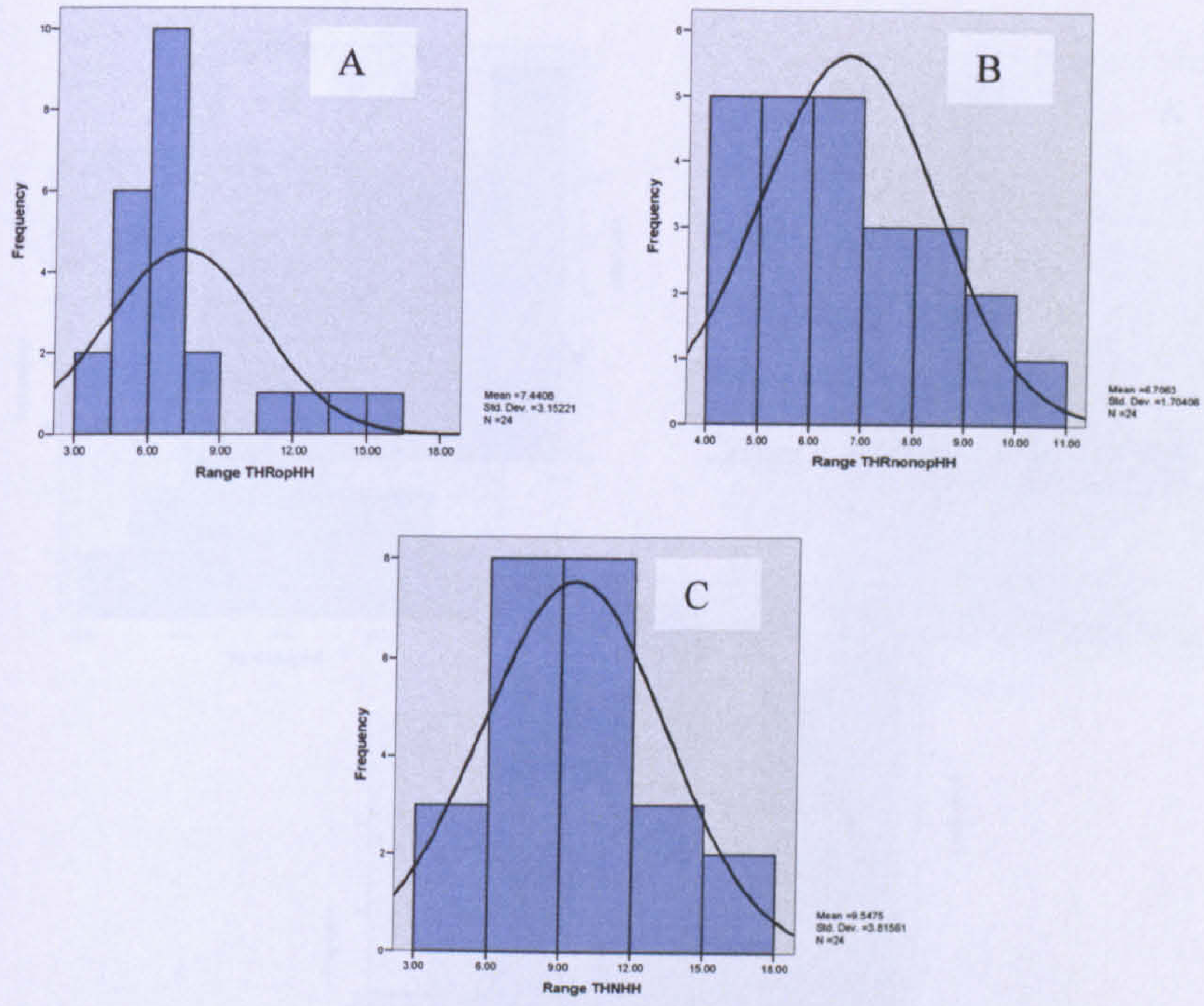
b) Normal Distribution plots



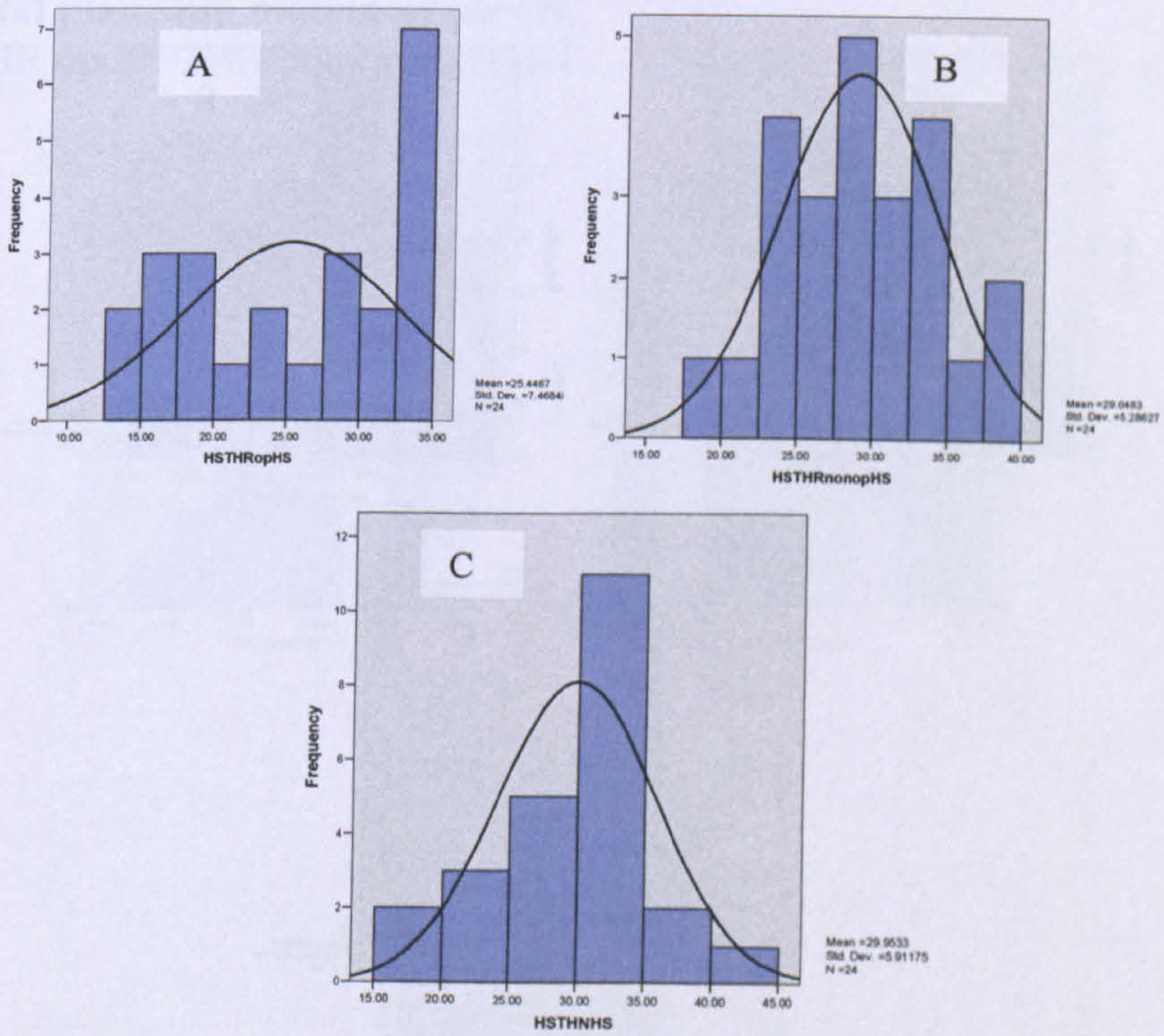
Range of sagittal plane hip motion
A: THR op, B: THR non op, C: THN



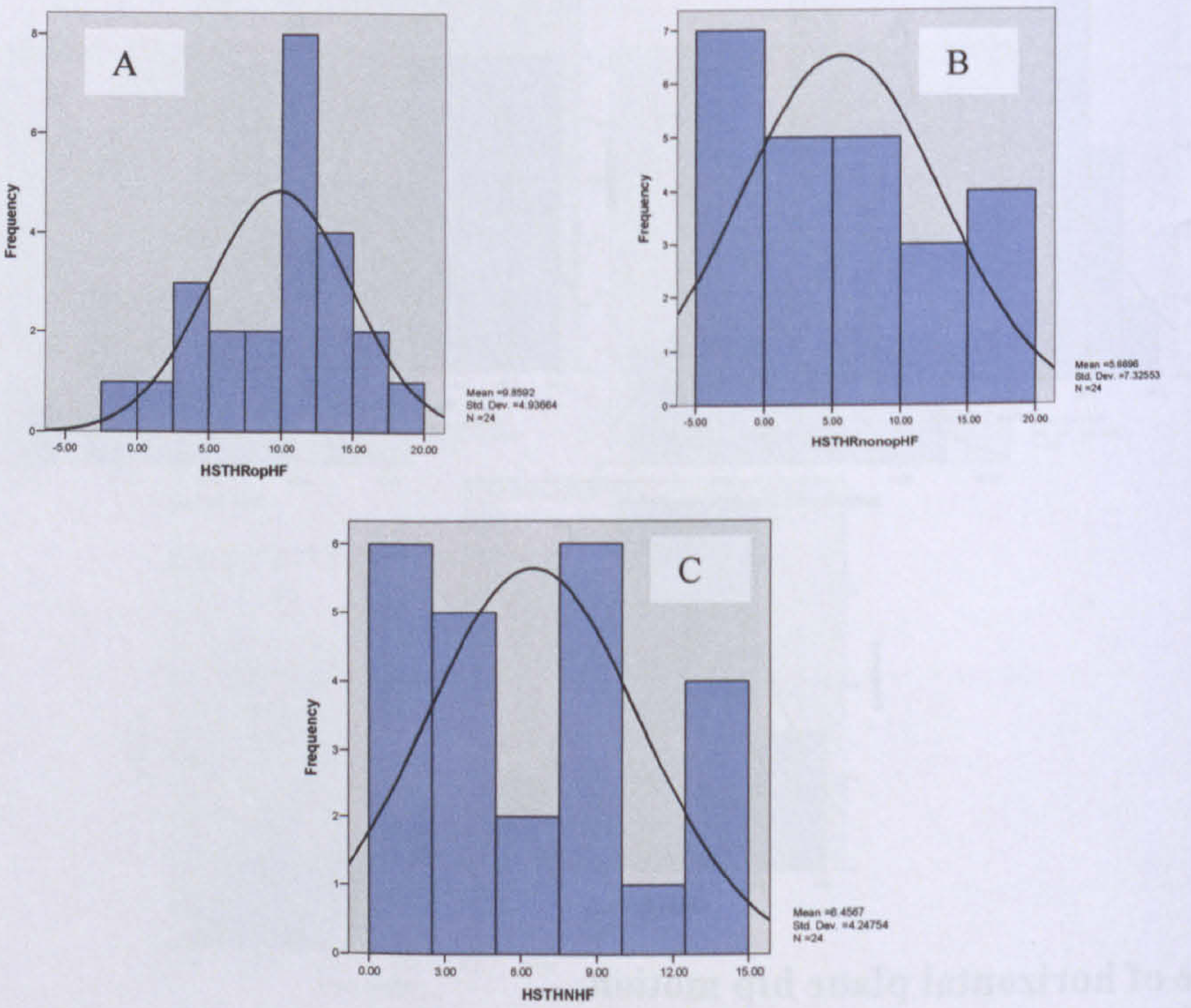
Range of frontal plane hip motion,
A: THR op, B: THR non op, C: THN



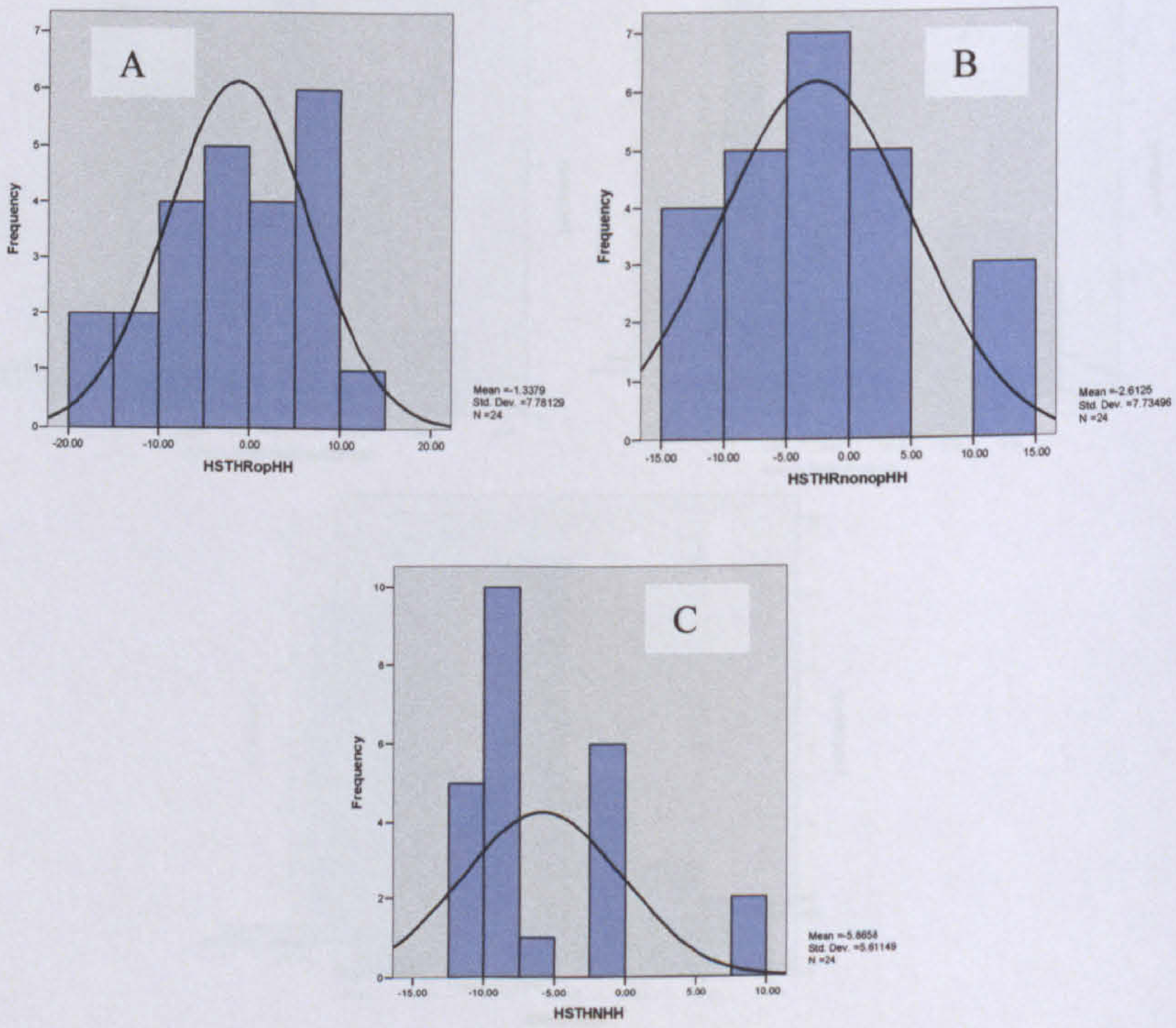
Range of horizontal plane hip motion,
A: THR op, B: THR non op, C: THN



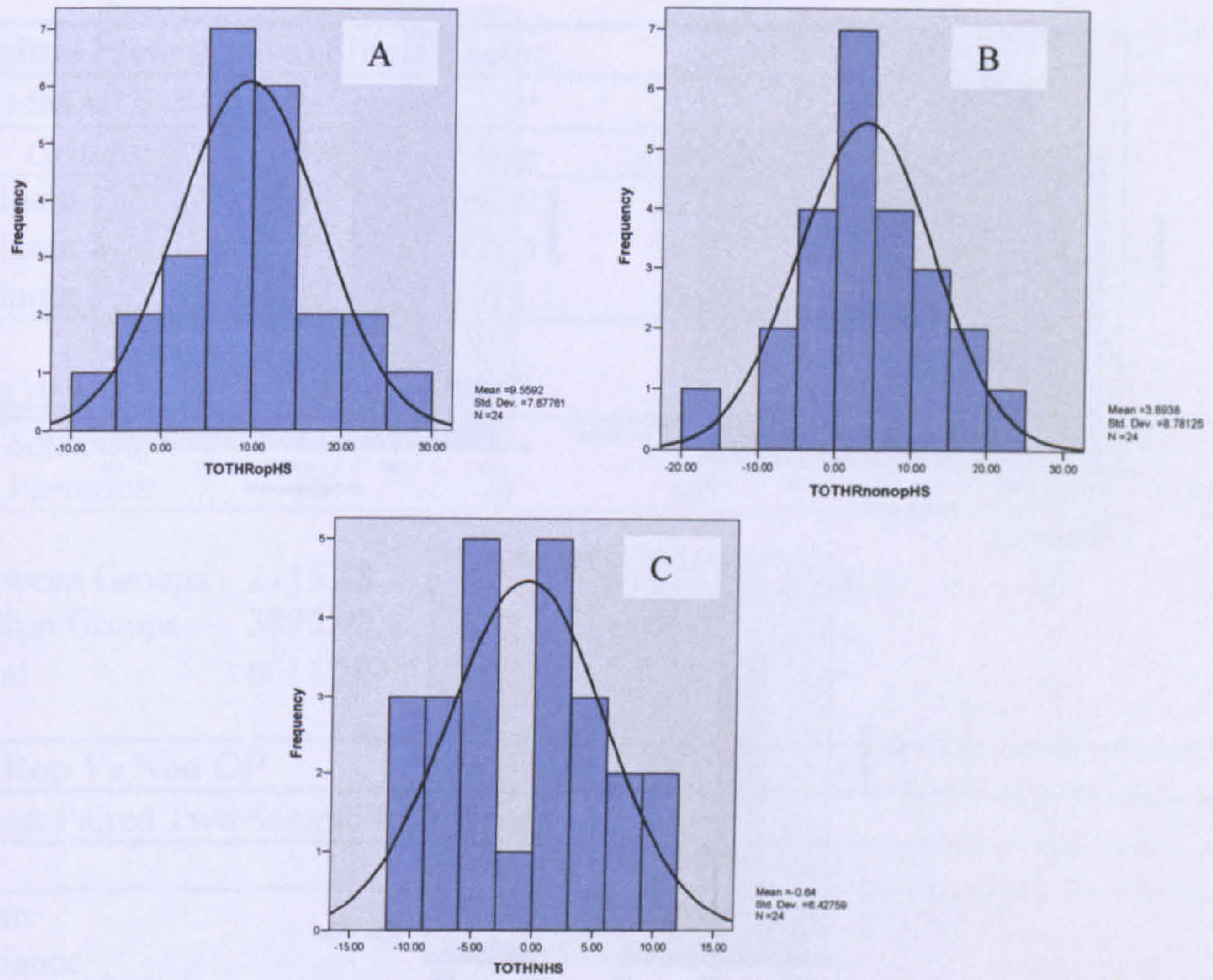
Sagittal plane hip motion at heel strike,
A: THR op, B: THR non op, C: THN



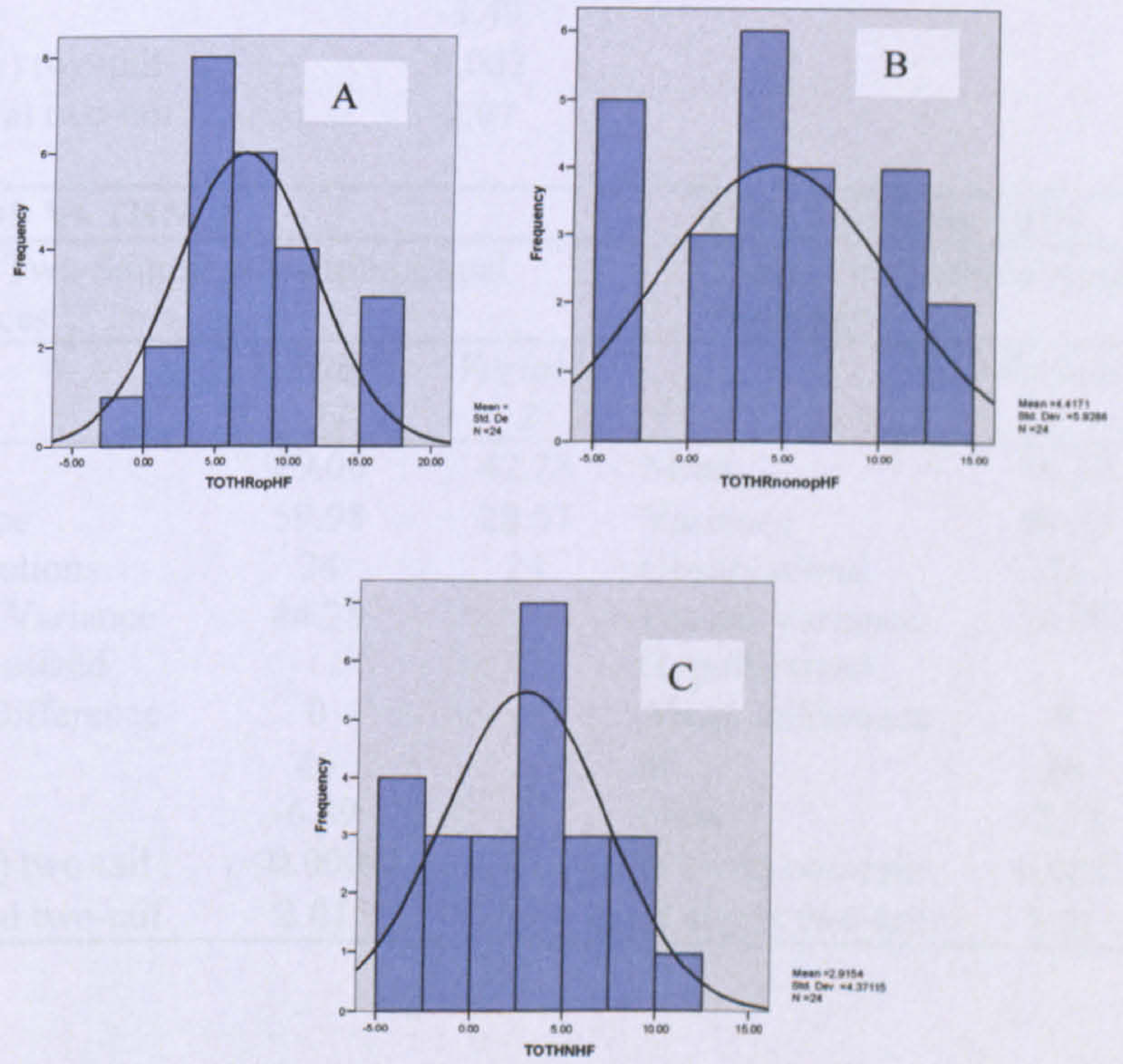
Frontal plane hip motion at heel strike,
A: THR op, B: THR non op, C: THN



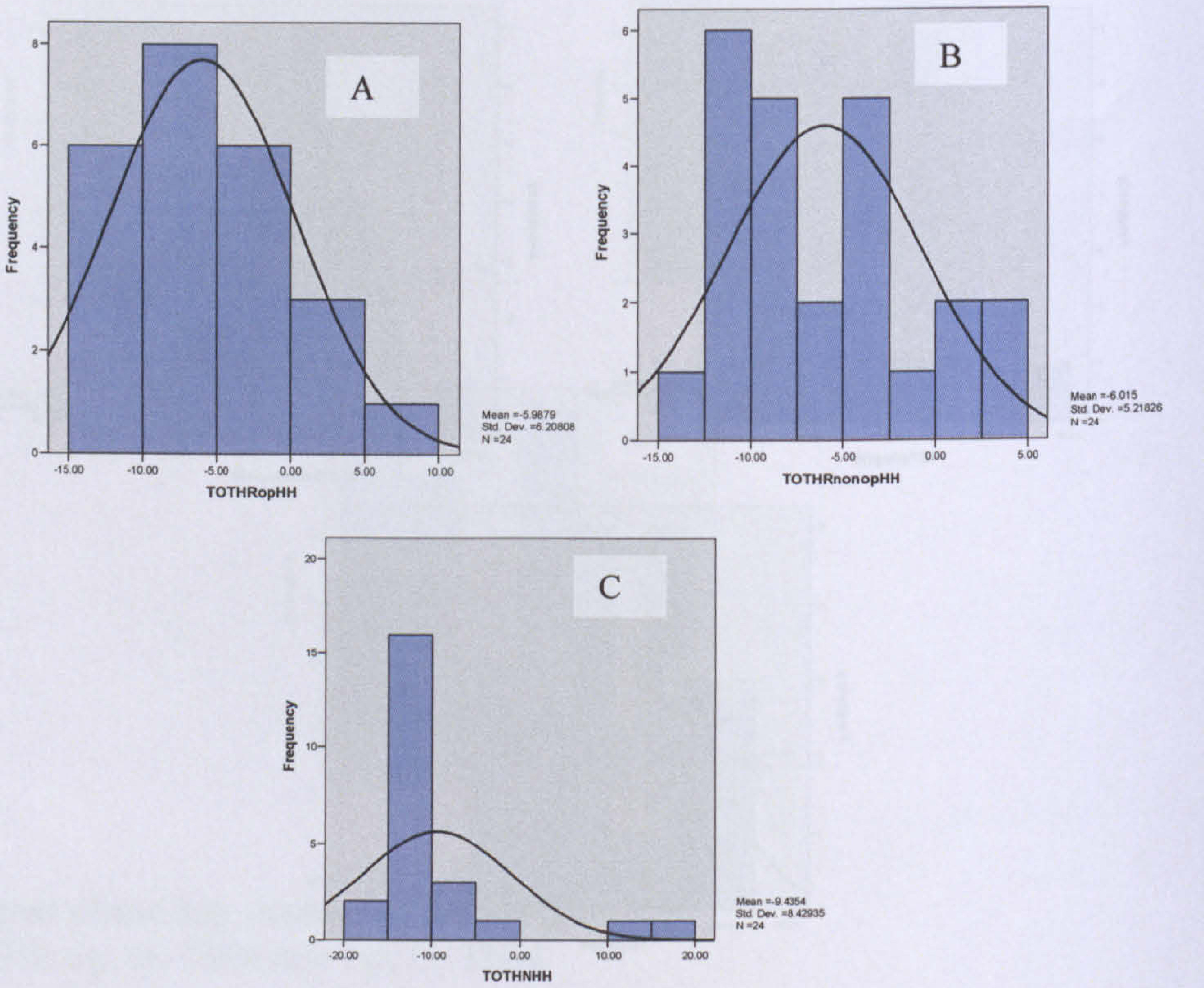
Horizontal plane hip motion at heel strike,
A: THR op, B: THR non op, C: THN



Sagittal plane hip motion at toe off,
A: THR op, B: THR non op, C: THN



Frontal plane hip motion at toe off,
A: THR op, B: THR non op, C: THN



Horizontal plane hip motion at toe off,
A: THR op, B: THR non op, C: THN

3) Statistical Analysis

a) Range of Sagittal Plane movement One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Sagittal Plane Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	696.03	29.00	59.98
Column 2	24	871.51	36.31	80.83
Column 3	24	1014.1	42.26	28.57

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2115.38	2	1057.69	18.73	0.0000003	3.13
Within Groups	3895.92	69	56.46			
Total	6011.29	71				

THRop Vs Non OP

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	29.00	36.31
Variance	59.98	80.83
Observations	24	24
Pearson Correlation	0.26	
Hypothesized Mean Difference	0	
df	23	
t Stat	-3.49	
P(T<=t) two-tail	0.002	
t Critical two-tail	2.07	

THROP Vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	29.00	42.25
Variance	59.98	28.57
Observations	24	24
Pooled Variance	44.28	
Hypothesized Mean Difference	0	
df	46	
t Stat	-6.89	
P(T<=t) two-tail	p<0.00001	
t Critical two-tail	2.01	

THR Non Opvs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	36.31	42.26
Variance	80.83	28.57
Observations	24	24
Pooled Variance	54.70	
Hypothesized Mean Difference	0	
df	46	
t Stat	-2.78	
P(T<=t) two-tail	0.008	
t Critical two-tail	2.01	

b) Range of Frontal Plane movement One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Frontal Plane Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	187.96	7.83	8.34
Column 2	24	195.27	8.14	6.27
Column 3	24	278.58	11.61	19.89

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	211.19	2	105.59	9.18	0.0003	3.13
Within Groups	793.44	69	11.49			
Total	1004.63	71				

THRop Vs Non OP

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	7.83183	8.136327
Variance	8.337194	6.272517
Observations	24	24
Pearson Correlation	0.27967	
Hypothesized Mean Difference	0	
df	23	
t Stat	-0.45894	
P(T<=t) one-tail	0.325292	
t Critical two-tail	2.068658	

THROP Vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	7.83	11.61
Variance	8.34	19.89
Observations	24	24
Pooled Variance	14.11	
Hypothesized Mean Difference	0	
df	46	
t Stat	-3.48	
P(T<=t) two-tail	0.001	
t Critical two-tail	2.013	

THR Non Opvs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	8.14	11.61
Variance	6.27	19.89
Observations	24	24
Pooled Variance	13.08	
Hypothesized Mean Difference	0	
df	46	
t Stat	-3.33	
P(T<=t) two-tail	0.002	
t Critical two-tail	2.013	

c) Range of Horizontal Plane movement One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Horizontal Plane Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	178.57	7.44	9.94
Column 2	24	160.97	6.71	2.90
Column 3	24	229.16	9.55	14.55

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	104.42	2	52.21	5.72	0.005	3.13
Within Groups	630.09	69	9.13			
Total	734.51	71				

THRop Vs Non OP

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	7.44	6.70
Variance	9.94	2.90
Observations	24	24
Pearson Correlation	0.43	
Hypothesized Mean Difference	0	
Df	23	
t Stat	1.25	
P(T<=t) two-tail	0.22	
t Critical two-tail	2.07	

THROP Vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	7.44	9.55
Variance	9.939	14.55
Observations	24	24
Pooled Variance	12.25	
Hypothesized Mean Difference	0	
Df	46	
t Stat	-2.09	
P(T<=t) two-tail	0.04	
t Critical two-tail	2.01	

THR Non Opvs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	6.71	9.55
Variance	2.90	14.55
Observations	24	24
Pooled Variance	8.73	
Hypothesized Mean Difference	0	
df	46	
t Stat	-3.33	
P(T<=t) two-tail	0.0017	
t Critical two-tail	2.01	

Appendix S: Biomechanical Pelvic movement

1) Raw Data (n = 24 per group (THR and THN)

a) Range of motion from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non OP	THN	THR Op	THR Non Op	THN
	3.67	3.67	3.95	6.53	6.53	3.32	6.30	6.30	7.05
	2.81	4.35	3.50	4.98	4.64	3.50	10.83	13.29	11.57
	5.61	4.58	5.02	3.78	4.81	3.84	6.59	6.47	9.80
	4.07	3.61	5.50	6.13	4.58	2.75	5.73	11.37	7.51
	2.12	3.15	4.87	3.27	3.20	3.09	9.45	7.10	4.47
	3.67	4.87	3.27	3.84	7.85	5.67	9.74	12.30	7.95
	3.44	2.23	2.06	3.90	5.44	4.70	6.59	4.53	4.58
	1.95	2.06	5.32	4.13	4.01	5.21	4.47	7.96	10.08
	5.96	3.04	3.38	6.19	6.53	3.69	10.27	12.45	8.74
	4.39	3.33	1.89	3.78	4.63	2.23	5.87	9.27	4.21
	2.35	2.35	2.58	2.41	2.41	5.61	8.78	8.78	8.14
	5.79	4.70	4.53	4.41	4.98	2.98	8.48	9.17	11.46
	4.73	4.82	4.47	6.99	6.56	6.12	6.76	8.45	7.68
	3.95	3.95	2.46	5.04	5.04	4.47	6.55	6.55	11.12
	2.81	2.86	4.87	5.33	7.28	5.99	8.87	8.44	7.45
	3.97	2.64	3.61	4.47	3.50	5.51	6.76	6.92	11.04
	4.54	2.81	3.50	1.20	2.18	6.18	4.69	8.08	7.21
	3.67	2.18	1.66	4.87	2.29	3.67	8.92	5.71	9.33
	3.27	4.41	5.34	3.04	2.98	4.41	9.40	12.79	11.45
	4.70	3.27	4.92	5.90	4.64	2.75	6.57	5.10	7.51
	3.53	3.95	5.17	5.04	5.04	4.84	6.83	6.55	4.80
	4.18	4.88	4.00	6.79	6.26	3.04	8.19	7.16	6.93
	2.67	3.15	5.16	3.50	2.64	4.76	5.65	7.57	7.28
	6.30	4.35	1.97	1.43	3.15	8.98	6.53	6.02	7.25
Mean	3.92	3.55	3.87	4.46	4.63	4.47	7.45	8.26	8.11
SD	1.19	0.93	1.25	1.56	1.63	1.53	1.77	2.51	2.27

b) Hip position at Heel Strike from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR OP	THR Non Op	THN
	-2.35	-2.35	11.63	-0.74	-0.74	0.74	-5.27	-5.27	3.95
	10.49	7.56	1.99	-4.41	4.87	-0.92	2.75	9.11	-8.08
	-0.57	2.41	-1.03	-3.04	0.69	3.38	0.97	-5.73	1.78
	10.37	11.00	2.64	-2.41	-1.55	2.29	7.79	-3.55	1.95
	11.34	12.26	4.01	-3.50	3.32	-0.63	7.68	-0.29	-7.79
	8.75	9.65	8.31	2.92	-1.72	-2.64	-4.18	1.32	3.56
	1.49	2.01	4.53	-1.15	-0.17	0.17	6.65	-1.03	-2.41
	8.82	9.74	-2.35	-1.03	-1.09	0.17	-3.78	6.70	1.15
	8.25	6.76	13.87	1.26	-0.57	-0.17	8.14	-8.25	-0.52
	0.69	4.01	-4.76	-5.04	7.85	1.20	-2.58	1.09	-0.86
	10.36	10.36	-4.13	-0.57	-0.57	6.65	-5.39	-5.39	6.76
	7.96	12.83	-3.55	-0.86	1.15	0.40	0.11	6.82	2.01
	9.45	10.06	4.46	7.73	-10.91	-6.47	-3.72	4.76	-2.41
	-2.50	-2.50	1.86	-2.69	-2.69	1.26	-10.77	-10.77	3.67
	1.43	4.07	10.60	2.12	-3.67	6.36	-0.91	0.35	3.84
	-2.59	1.32	-1.78	-11.12	9.40	-6.99	3.61	-5.39	-9.28
	-0.70	5.27	8.25	-1.20	1.55	-0.52	-1.20	-1.15	5.73
	7.85	6.93	7.22	-2.01	0.34	-0.92	1.09	-6.00	3.09
	6.76	6.59	-1.03	-3.72	5.39	6.25	6.71	1.20	0.91
	12.70	14.27	2.23	-0.23	4.98	2.29	-6.53	4.30	1.95
	-1.50	-2.50	3.14	-1.69	-2.69	-4.84	8.77	-10.77	4.80
	-0.06	-1.72	5.38	3.67	-3.44	-1.32	3.15	-4.28	1.60
	2.49	7.24	5.33	-3.32	1.49	2.69	-0.36	4.26	-0.36
	10.37	13.46	12.66	0.52	-2.29	-0.40	-11.97	13.24	2.93
Mean	4.97	6.20	3.73	-1.27	0.37	0.34	0.03	-0.61	0.75
SD	5.29	5.26	5.36	3.55	4.24	3.49	5.89	6.23	4.21

c) Hip position at Toe Off from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Non Op	THR Op	THN
	-1.66	-1.66	8.08	4.35	4.35	2.23	-3.72	-3.72	-1.15
	9.85	9.4	3.83	6.42	-1.72	-0.69	-6.59	-3.44	-3.78
	-1.60	-0.92	-3.14	0.63	-0.74	0.86	5.04	-3.27	-2.44
	10.20	8.71	-2.58	-3.04	-1.38	2.69	8.48	-11.63	-2.58
	13.92	13.01	4.98	4.58	-1.83	1.82	0.17	-5.84	-6.06
	9.42	7.77	10.94	2.75	2.69	-0.8	-1.26	-2.34	-3.09
	0.19	0.57	5.44	1.72	-0.01	2.98	1.26	-4.07	-3.5
	8.48	9.05	-4.07	0.69	1.55	1.03	-6.47	-0.69	-2.75
	7.05	4.76	13.18	2.52	3.5	0.774	5.9	-12.03	-1.6
	2.69	-0.24	-4.64	8.14	-5.2	0.8	-2.93	-0.69	0.34
	11.10	11.10	-3.95	-2.35	-2.35	6.59	-1.2	-1.2	5.61
	9.17	12.15	-0.86	2.58	1.66	-1.32	-5.61	0.01	-1.32
	7.10	13.00	1.82	-7.68	11	-2.3	-4.07	4.47	-2.4
	-0.32	0.24	2.78	0.52	0.4	-1.83	-11.69	11.29	-5.39
	2.23	1.78	11.99	0.63	6.07	9.28	-4.8	-2.25	-1.2
	0.06	0.69	-1.60	10.14	-11.57	-5.1	0.57	-6.7	-14.9
	2.81	1.93	7.16	2.12	-1.15	3.96	-0.17	-5.14	1.32
	5.10	9.45	6.53	-0.34	0.19	-0.4	-2.58	-2.18	-5.6
	6.70	6.02	-1.95	5.73	-3.27	4.53	-0.11	-11.1	-7.39
	15.07	13.38	-2.38	1.26	-0.57	2.69	-11.3	8.31	-2.58
	-0.32	1.14	5.60	0.52	1.57	-2.06	8.77	-11.29	0.68
	0.11	-3.67	6.07	-4.93	5.9	0.17	-0.8	-4.98	-4.98
	4.44	3.61	1.89	3.32	-1.43	0.74	-2.82	-1.49	-4.12
	10.08	13.64	13.78	-2.12	0.11	3.89	-13.35	10.03	-1.67
Mean	5.49	5.62	3.29	1.59	0.32	1.27	-2.05	-2.50	-2.94
SD	5.04	5.55	5.75	4.00	4.30	3.09	5.71	6.26	3.73

d) Mean Sagittal plane motion through the Gait Cycle (°) (n=24)

% Time	THR OP	THR Non OP	THN
0	4.97	6.20	3.73
2	4.99	6.22	3.79
4	4.95	6.20	3.78
6	4.80	6.03	3.61
8	4.58	5.78	3.39
10	4.49	5.65	3.34
12	4.48	5.54	3.27
14	4.48	5.52	3.26
16	4.61	5.57	3.29
18	4.78	5.67	3.36
20	4.94	5.67	3.44
22	5.04	5.75	3.48
24	5.14	5.79	3.55
26	5.22	5.79	3.59
28	5.29	5.84	3.63
30	5.41	5.87	3.74
32	5.56	5.98	3.83
34	5.69	6.06	3.90
36	5.84	6.17	3.98
38	5.91	6.22	4.01
40	5.91	6.17	4.04
42	5.95	6.12	3.98
44	5.99	6.06	3.89
46	6.04	5.99	3.86
48	6.10	5.89	3.87
50	6.14	5.91	3.83
52	6.21	5.95	3.77
54	6.23	5.91	3.68
56	6.19	5.88	3.61
58	6.04	5.83	3.52
60	5.87	5.71	3.47
62	5.74	5.75	3.40
64	5.70	5.79	3.39
66	5.77	5.88	3.50
68	5.84	6.00	3.60
70	5.81	6.13	3.68
72	5.79	6.12	3.77
74	5.75	6.17	3.84
76	5.77	6.23	3.92
78	5.86	6.32	4.05
80	5.95	6.39	4.14
82	5.98	6.43	4.19
84	6.09	6.52	4.18
86	6.14	6.57	4.19
88	6.15	6.62	4.16
90	6.16	6.62	4.10
92	6.14	6.57	4.05
94	6.09	6.57	4.02
96	6.02	6.57	3.98
98	5.86	6.50	3.94
100	5.69	6.43	3.85

e) Mean Frontal plane motion through the Gait Cycle (°) (n=24)

% Time	THR OP	THR Non OP	THN
0	-1.27	0.37	0.55
2	-1.30	0.22	0.35
4	-1.45	0.00	0.05
6	-1.69	-0.27	-0.30
8	-1.92	-0.55	-0.64
10	-2.13	-0.79	-0.86
12	-2.30	-0.90	-0.94
14	-2.31	-0.93	-0.97
16	-2.30	-0.88	-0.92
18	-2.17	-0.65	-0.78
20	-1.93	-0.40	-0.57
22	-1.65	-0.20	-0.33
24	-1.37	0.03	-0.08
26	-1.09	0.28	0.10
28	-0.80	0.53	0.24
30	-0.55	0.68	0.41
32	-0.37	0.82	0.48
34	-0.19	0.98	0.49
36	-0.11	1.13	0.44
38	-0.07	1.18	0.32
40	-0.07	1.22	0.14
42	-0.17	1.21	0.00
44	-0.29	1.15	0.12
46	-0.36	1.06	0.15
48	-0.46	0.99	0.15
50	-0.57	0.96	0.10
52	-0.51	1.03	0.20
54	-0.32	1.17	0.33
56	-0.15	1.34	0.58
58	0.01	1.57	0.80
60	0.21	1.75	1.07
62	0.38	1.85	1.20
64	0.41	1.89	1.30
66	0.44	1.82	1.25
68	0.31	1.71	1.10
70	0.11	1.60	1.00
72	-0.08	1.57	0.74
74	-0.22	1.47	0.43
76	-0.46	1.30	0.20
78	-0.70	1.15	0.07
80	-0.99	0.92	-0.06
82	-1.19	0.78	-0.20
84	-1.38	0.60	-0.10
86	-1.53	0.45	-0.03
88	-1.62	0.40	0.00
90	-1.62	0.37	-0.07
92	-1.59	0.41	-0.24
94	-1.57	0.40	-0.37
96	-1.55	0.40	-0.50
98	-1.54	0.46	-0.52
100	-1.52	0.44	-0.57

f) Mean Horizontal plane motion through the Gait Cycle (°) (n=24)

% Time	THR OP	THR Non OP	THN
0	0.03	-0.61	0.57
2	0.34	-0.45	0.74
4	0.52	-0.36	0.77
6	0.62	-0.37	0.72
8	0.70	-0.38	0.77
10	0.85	-0.31	0.85
12	1.00	-0.17	1.01
14	1.11	0.04	1.16
16	1.32	0.34	1.32
18	1.44	0.64	1.46
20	1.50	0.82	1.47
22	1.61	1.02	1.49
24	1.62	1.14	1.47
26	1.56	1.07	1.51
28	1.46	0.96	1.53
30	1.41	0.85	1.44
32	1.28	0.74	1.36
34	1.06	0.50	1.20
36	0.78	0.35	1.07
38	0.50	0.05	0.79
40	0.09	-0.40	0.43
42	-0.32	-0.89	0.00
44	-0.73	-1.37	-0.50
46	-1.06	-1.89	-1.06
48	-1.37	-2.28	-1.55
50	-1.63	-2.60	-2.03
52	-1.87	-2.83	-2.41
54	-1.97	-2.91	-2.59
56	-1.98	-2.93	-2.57
58	-1.94	-2.93	-2.57
60	-1.90	-3.13	-2.66
62	-1.99	-3.30	-2.82
64	-2.08	-3.45	-3.07
66	-2.21	-3.61	-3.33
68	-2.18	-3.67	-3.44
70	-2.24	-3.72	-3.44
72	-2.36	-3.85	-3.49
74	-2.41	-3.95	-3.48
76	-2.38	-3.89	-3.39
78	-2.28	-3.82	-3.22
80	-2.17	-3.80	-3.06
82	-2.11	-3.66	-2.91
84	-1.91	-3.50	-2.75
86	-1.79	-3.40	-2.45
88	-1.57	-3.21	-2.13
90	-1.22	-2.96	-1.77
92	-0.94	-2.56	-1.28
94	-0.62	-2.21	-0.74
96	-0.17	-1.86	-0.27
98	0.21	-1.59	0.12
100	0.59	-1.40	0.32

g) Mean THN Lumbar Spine planar motion through the Gait Cycle (°) (n=24)

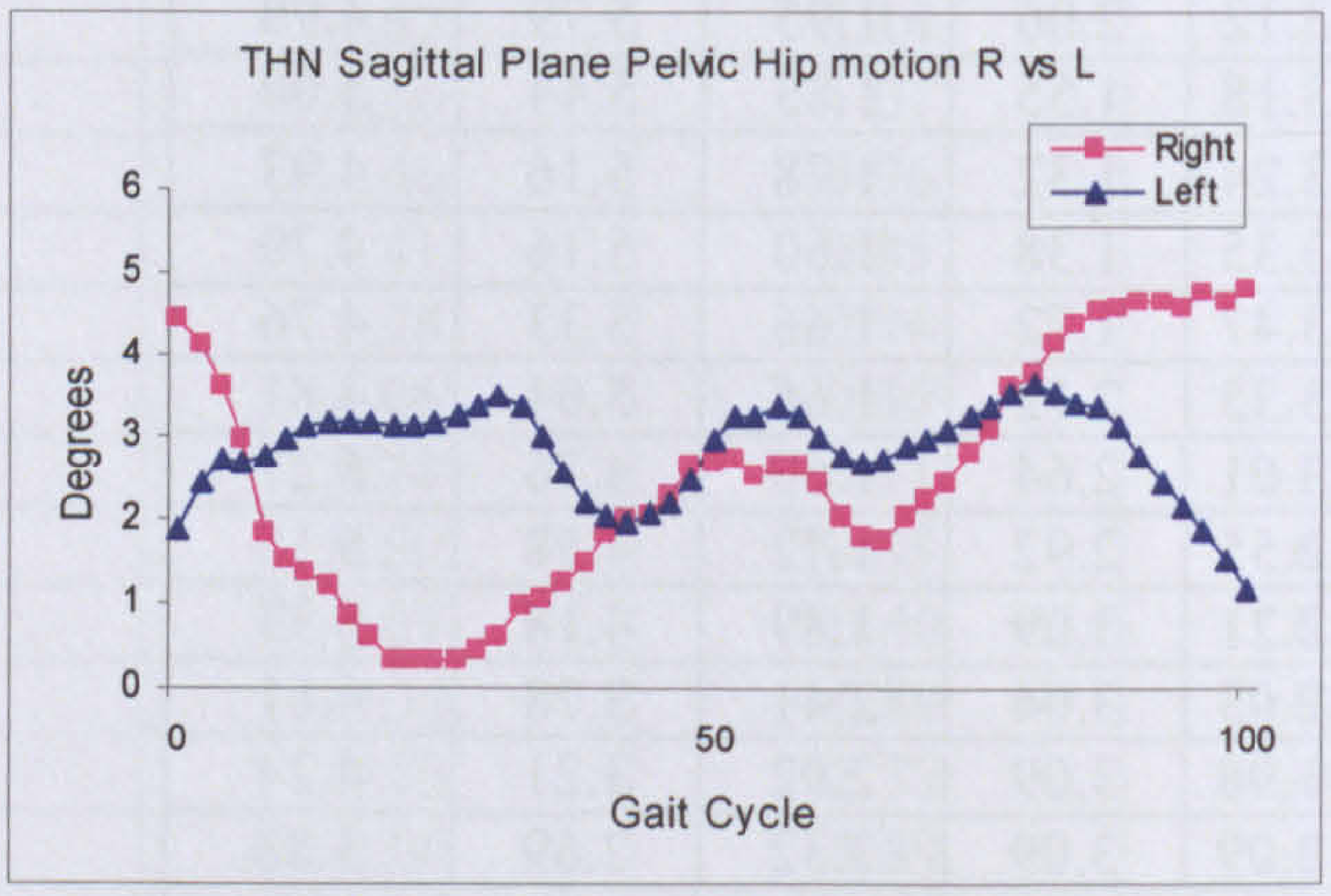
	Sagittal Plane		Frontal Plane		Horizontal Plane	
	Right	Left	Right	Left	Right	Left
0	4.46	1.86	0.17	0.92	5.73	3.60
2	4.11	2.44	0.06	1.55	5.79	3.75
4	3.60	2.72	0.86	2.41	5.84	4.20
6	2.97	2.66	1.55	3.21	6.02	4.53
8	1.82	2.78	2.12	3.61	6.30	5.13
10	1.54	2.95	2.92	3.61	6.59	5.45
12	1.36	3.12	3.67	3.44	6.91	5.45
14	1.19	3.18	4.18	3.21	6.99	5.61
16	0.85	3.18	3.95	2.86	6.65	5.33
18	0.62	3.18	3.38	2.46	6.19	4.98
20	0.33	3.12	2.69	2.18	5.84	5.13
22	0.33	3.12	2.06	1.95	5.79	4.98
24	0.33	3.18	1.55	1.83	5.44	5.00
26	0.33	3.24	1.32	1.78	5.16	4.93
28	0.45	3.35	1.38	1.60	5.16	4.70
30	0.62	3.47	1.72	1.66	5.33	4.76
32	0.96	3.35	2.12	1.66	5.04	4.81
34	1.02	3.01	2.64	1.60	4.76	5.27
36	1.25	2.55	2.92	1.72	4.58	5.15
38	1.48	2.21	3.09	1.89	4.18	5.33
40	1.82	2.03	3.04	2.41	3.78	4.61
42	1.99	1.98	3.09	2.92	3.21	4.24
44	2.05	2.09	3.09	3.32	2.69	3.88
46	2.28	2.21	2.98	3.55	2.41	3.82
48	2.63	2.49	2.81	3.78	2.01	3.76
50	2.68	2.95	2.29	3.61	1.83	3.34
52	2.74	3.24	1.66	3.15	1.38	3.28
54	2.51	3.24	0.80	2.29	1.09	2.86
56	2.63	3.35	-0.01	1.55	1.20	2.60
58	2.63	3.24	-0.52	0.80	1.38	2.26
60	2.45	3.01	-0.97	0.23	1.32	2.56
62	2.05	2.78	-1.03	0.11	1.09	3.10
64	1.82	2.66	-0.46	0.17	1.20	3.87
66	1.76	2.72	0.01	0.40	1.55	4.46
68	2.05	2.89	0.29	0.74	2.18	5.60
70	2.22	2.95	0.80	1.09	2.86	6.00
72	2.45	3.07	1.26	1.26	4.18	6.24
74	2.80	3.24	1.43	1.38	4.93	6.36
76	3.08	3.35	1.32	1.49	5.84	6.85
78	3.60	3.52	1.26	1.66	6.25	7.33
80	3.77	3.64	1.38	1.83	6.02	7.52
82	4.11	3.52	1.55	2.06	5.61	7.51
84	4.34	3.41	1.43	2.12	5.33	7.64
86	4.52	3.35	1.15	2.12	5.54	7.39
88	4.57	3.12	1.09	2.01	6.14	6.67
90	4.63	2.78	1.03	1.72	6.95	5.67
92	4.63	2.44	0.69	1.38	7.48	3.52
94	4.57	2.15	0.52	1.09	8.00	2.40
96	4.74	1.86	0.40	0.74	8.30	2.03
98	4.63	1.52	0.40	0.57	7.82	2.24
100	4.80	1.17	0.22	0.92	6.82	2.71

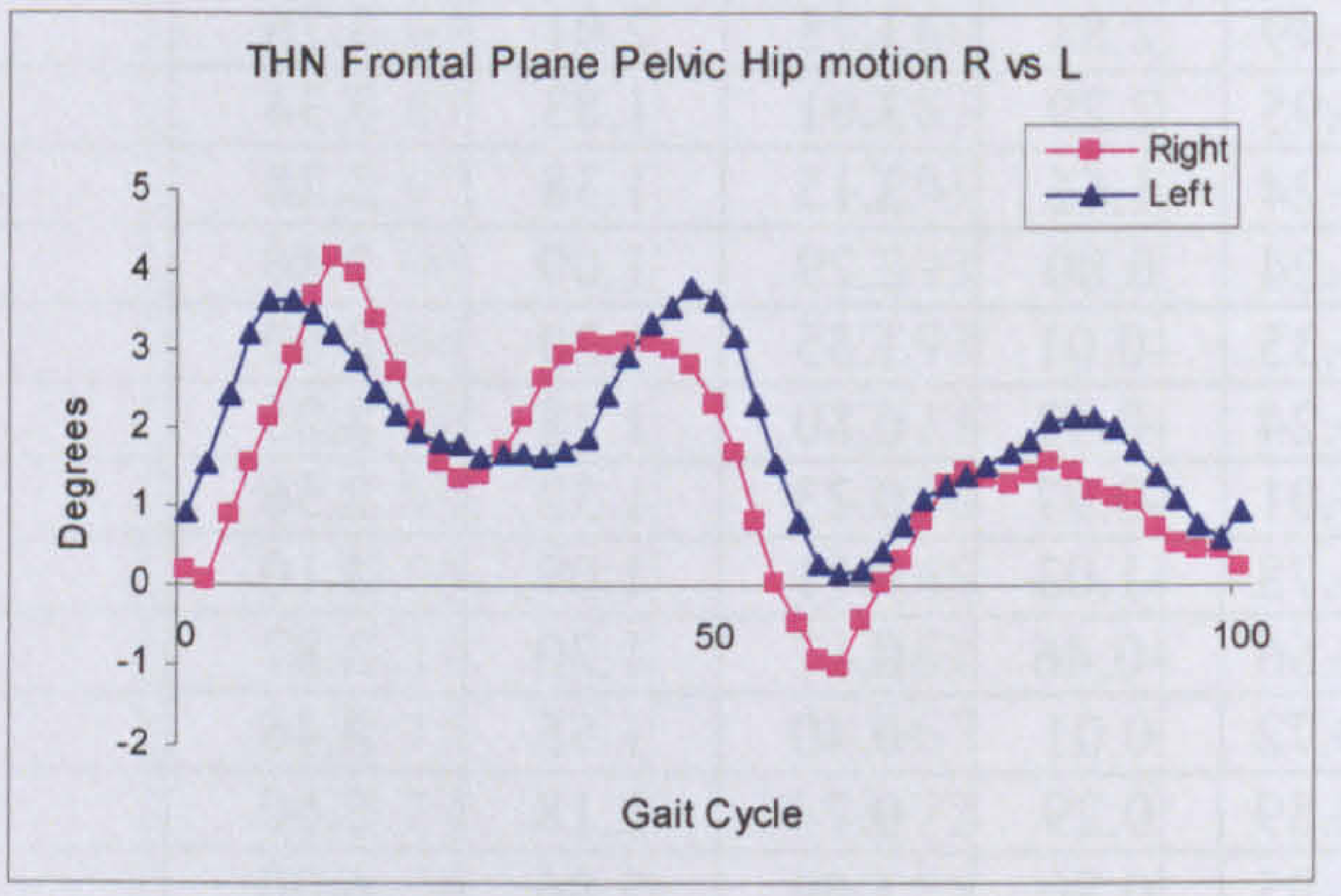
Pelvic movement, comparison of left and right sided data during walking

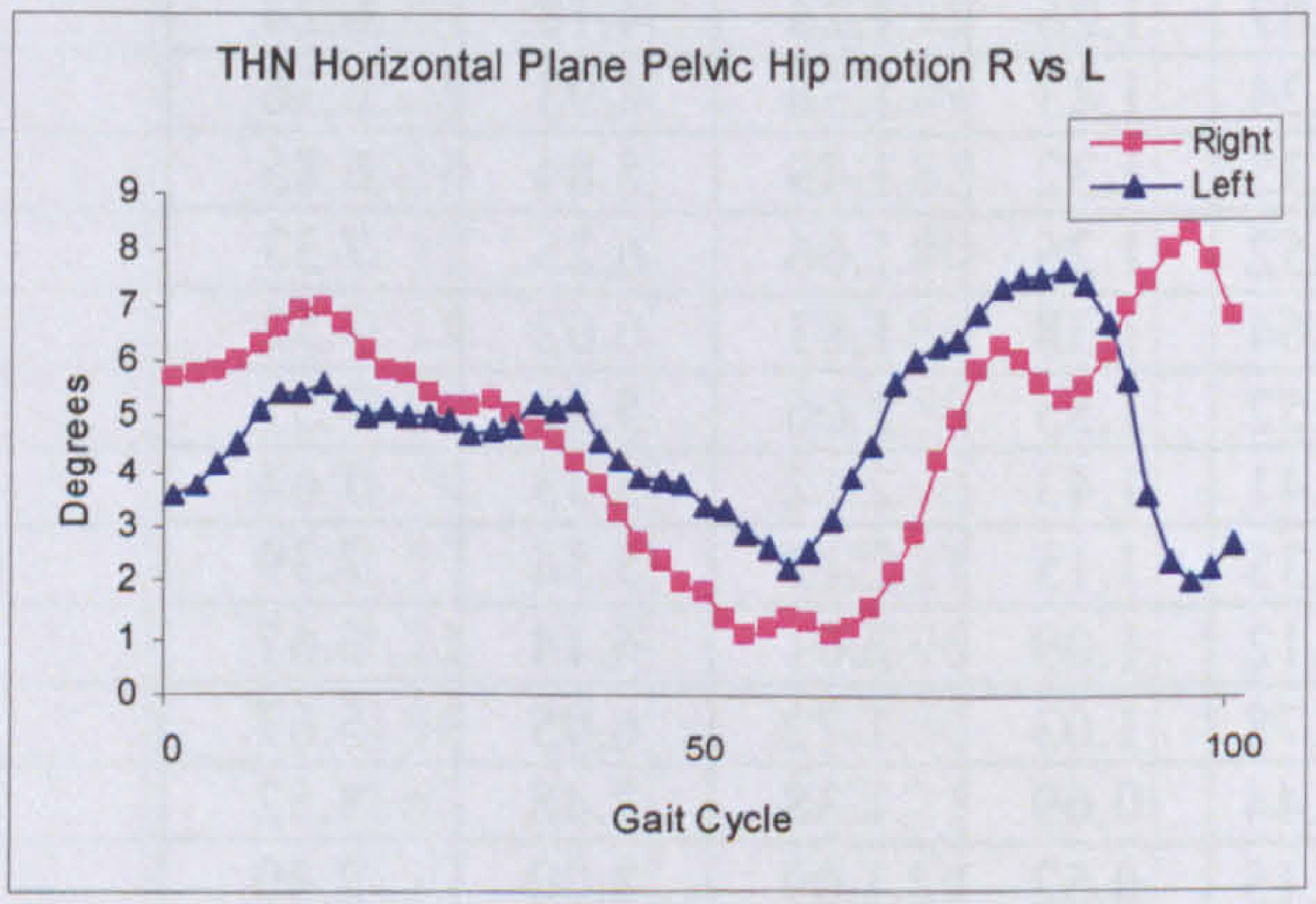
Two sample t-test between THN right and left data sets

	t value	p value
Sagittal	-1.59	0.11
Frontal	-1.75	0.08
Horizontal	0.029	0.98

No significant difference between right and left data sets for pelvic data for each plane, tested by two sample t-test, significance set at $p \leq 0.05$







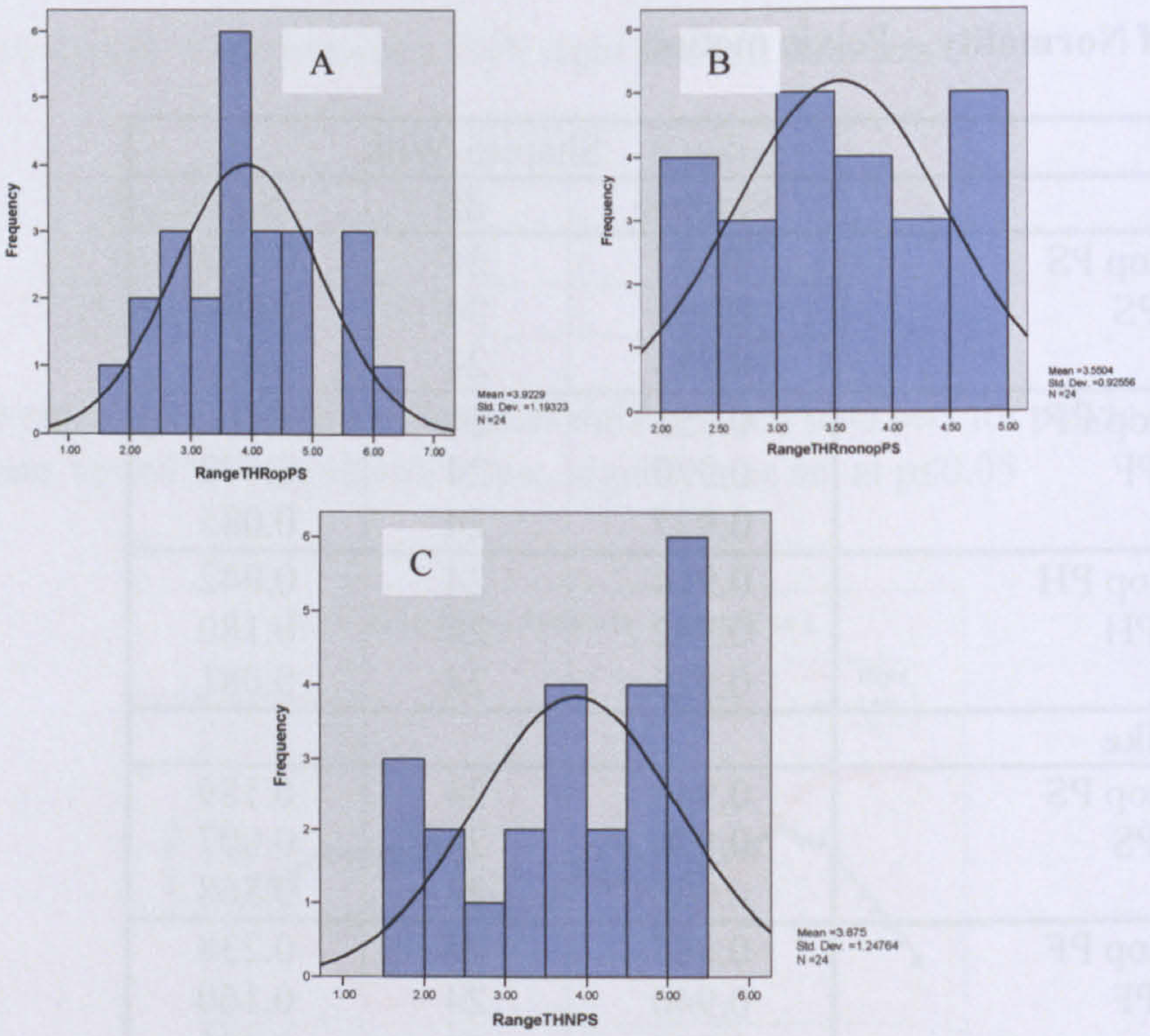
2) Test for Normal Distribution

a) Tests of Normality – Pelvic motion

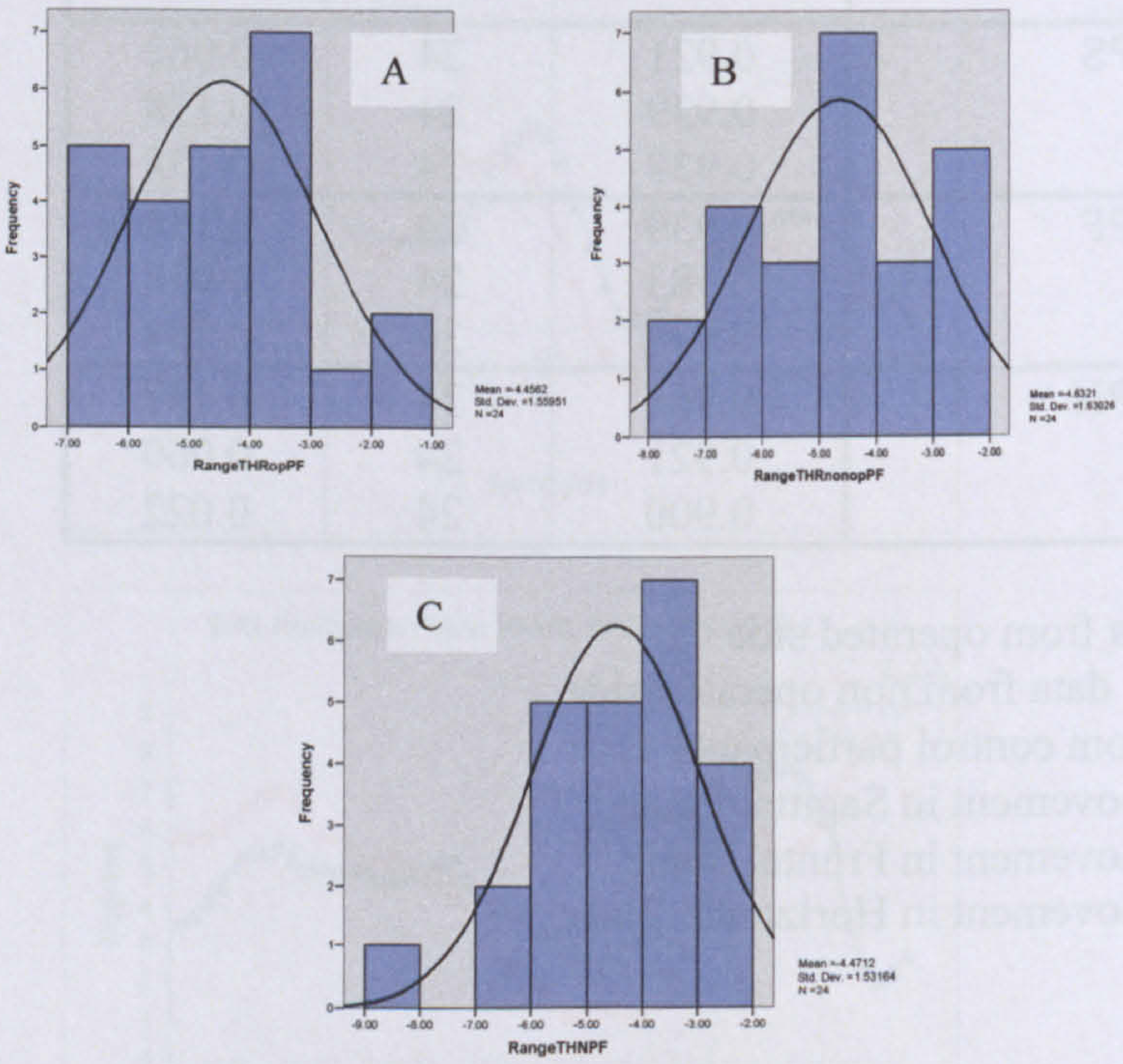
	Shapiro-Wilk		
Range	Statistic	df	Sig.
THR nonop PS	0.937	24	0.139
THR op PS	0.966	24	0.576
THN PS	0.913	24	0.041
THR nonop PF	0.955	24	0.348
THR op PF	0.970	24	0.672
THN PF	0.927	24	0.085
THR nonop PH	0.914	24	0.042
THR op PH	0.942	24	0.180
THN PH	0.926	24	0.081
Heel Strike			
THR nonop PS	0.943	24	0.189
THR op PS	0.876	24	0.007
THN PS	0.966	24	0.568
THR nonop PF	0.947	24	0.238
THR op PF	0.940	24	0.160
THN PF	0.944	24	0.201
THR nonop PH	0.973	24	0.748
THR op PH	0.958	24	0.404
THN PH	0.874	24	0.006
Toe Off			
THR nonop PS	0.921	24	0.062
THR op PS	0.939	24	0.158
THN PS	0.937	24	0.138
THR nonop PF	0.939	24	0.158
THR op PF	0.983	24	0.938
THN PF	0.973	24	0.744
THR nonop PH	0.965	24	0.537
THR op PH	0.921	24	0.060
THN PH	0.900	24	0.022

THR op – data from operated side
THR non op - data from non operated side
THN - data from control participants
PS – Pelvic movement in Sagittal Plane
PF – Pelvic movement in Frontal Plane
PH - Pelvic movement in Horizontal Plane

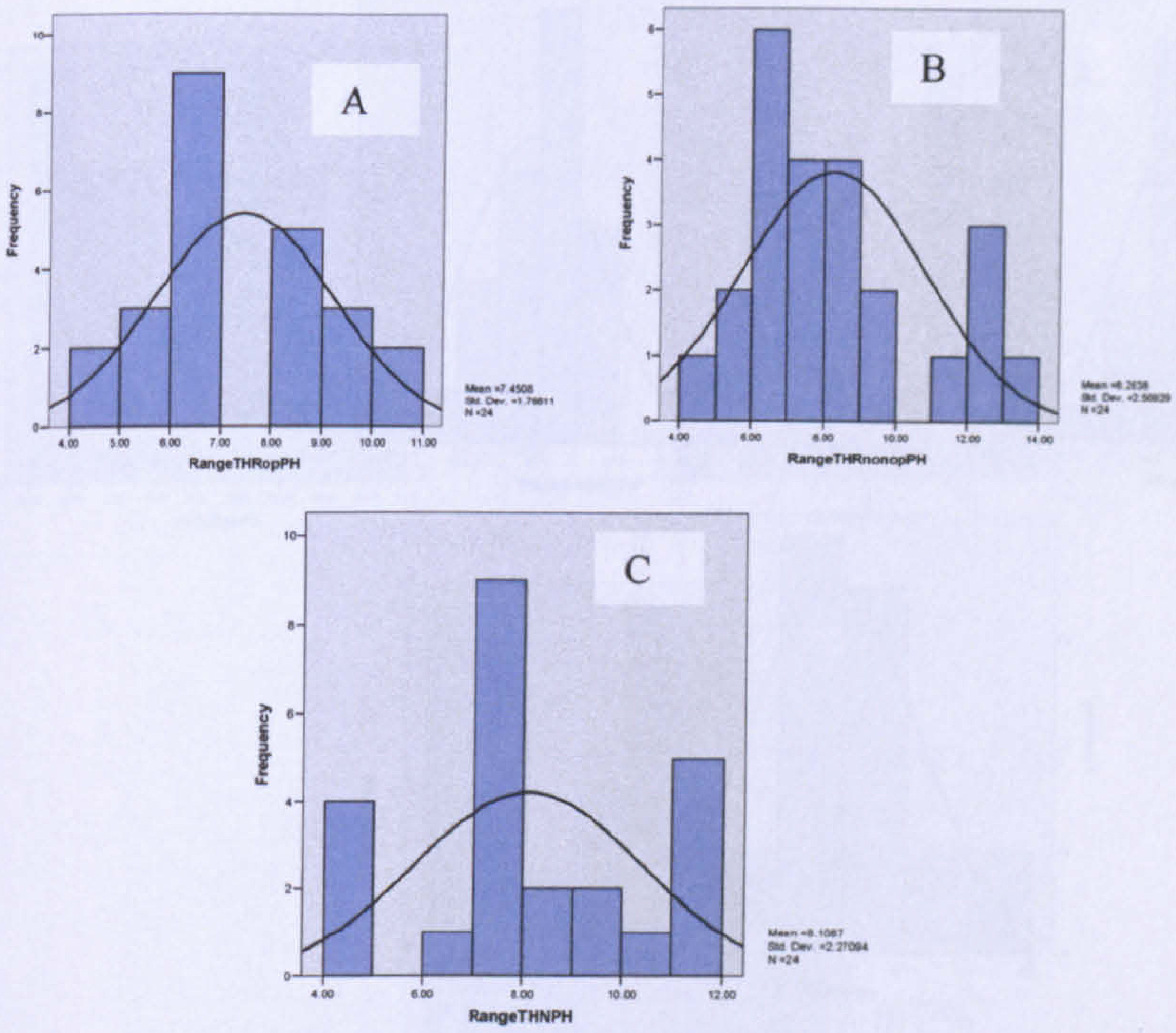
b) Normal Distribution plots



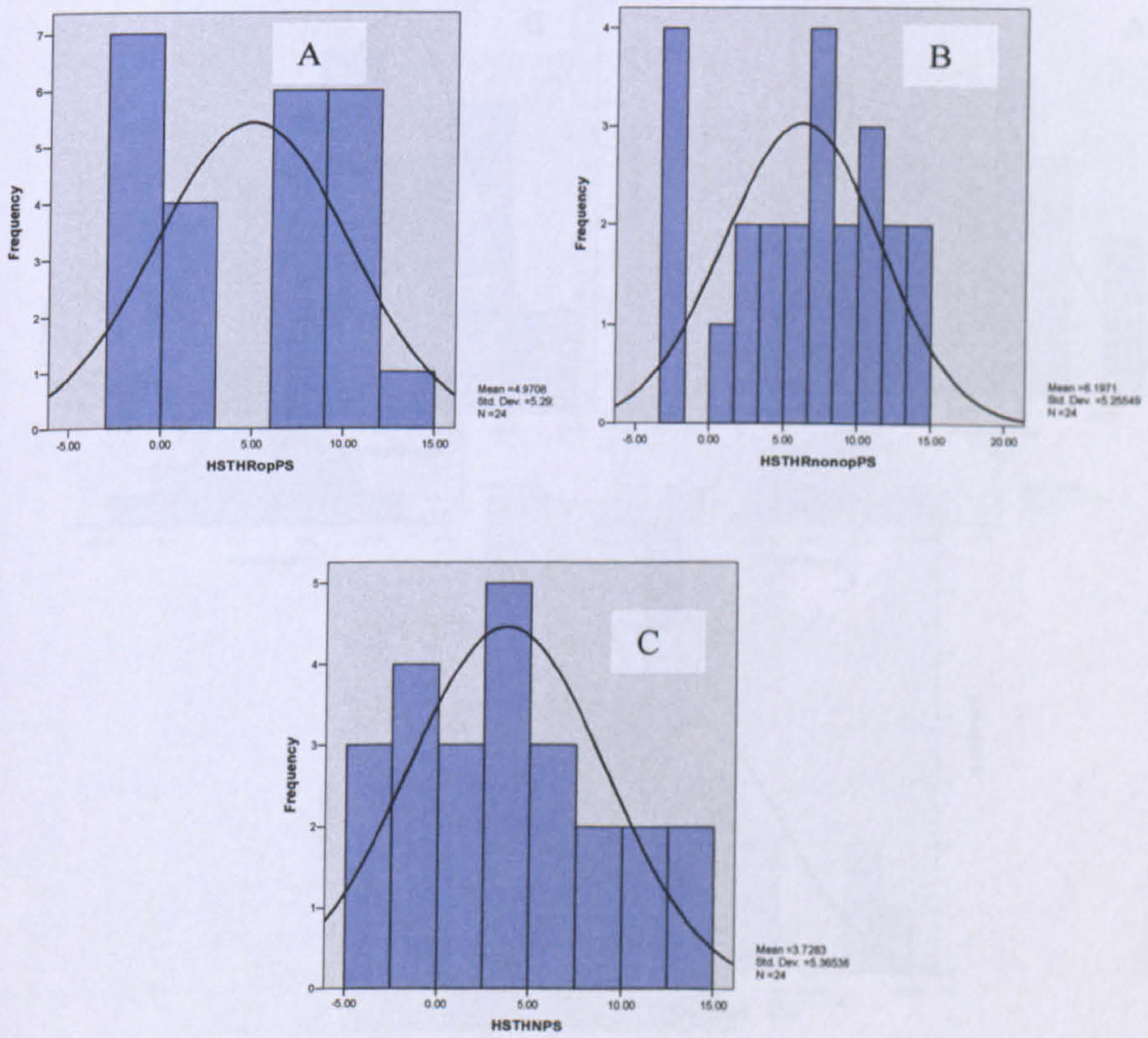
Range of sagittal plane lumbar spine motion,
A: THR op, B: THR non op, C: THN



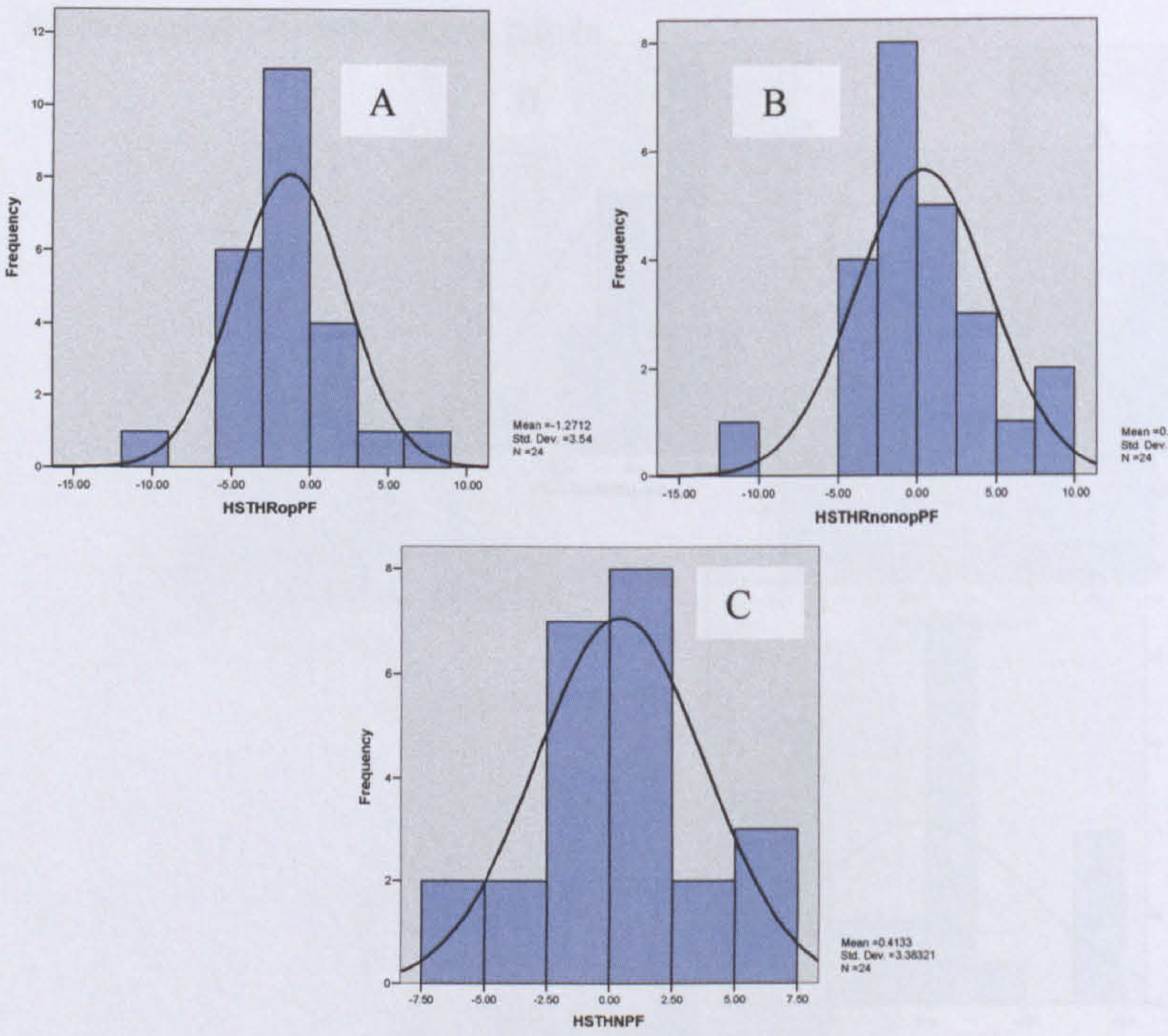
Range of frontal plane lumbar spine motion,
A: THR op, B: THR non op, C: THN



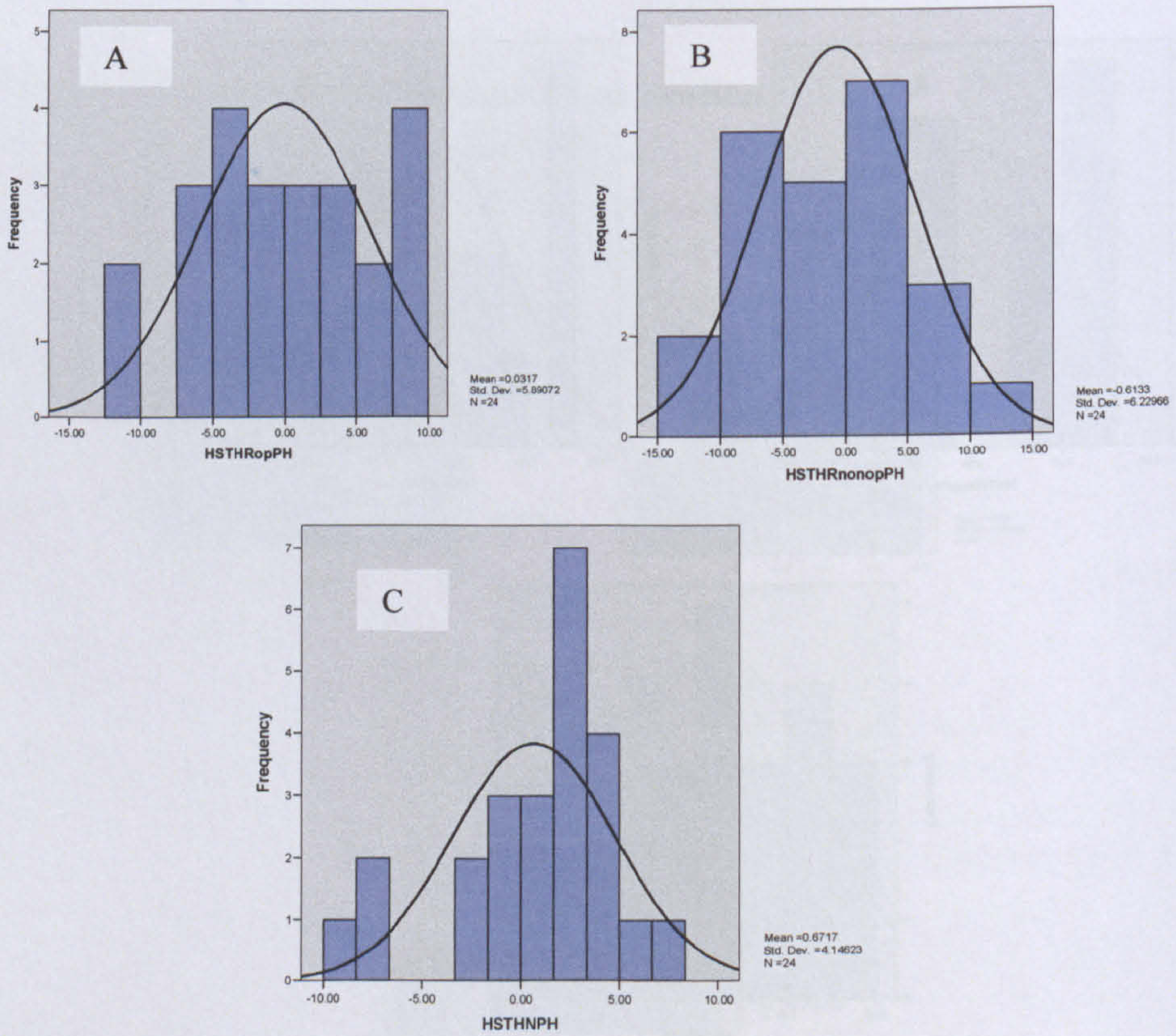
Range of horizontal plane lumbar spine motion,
A: THR op, B: THR non op, C: THN



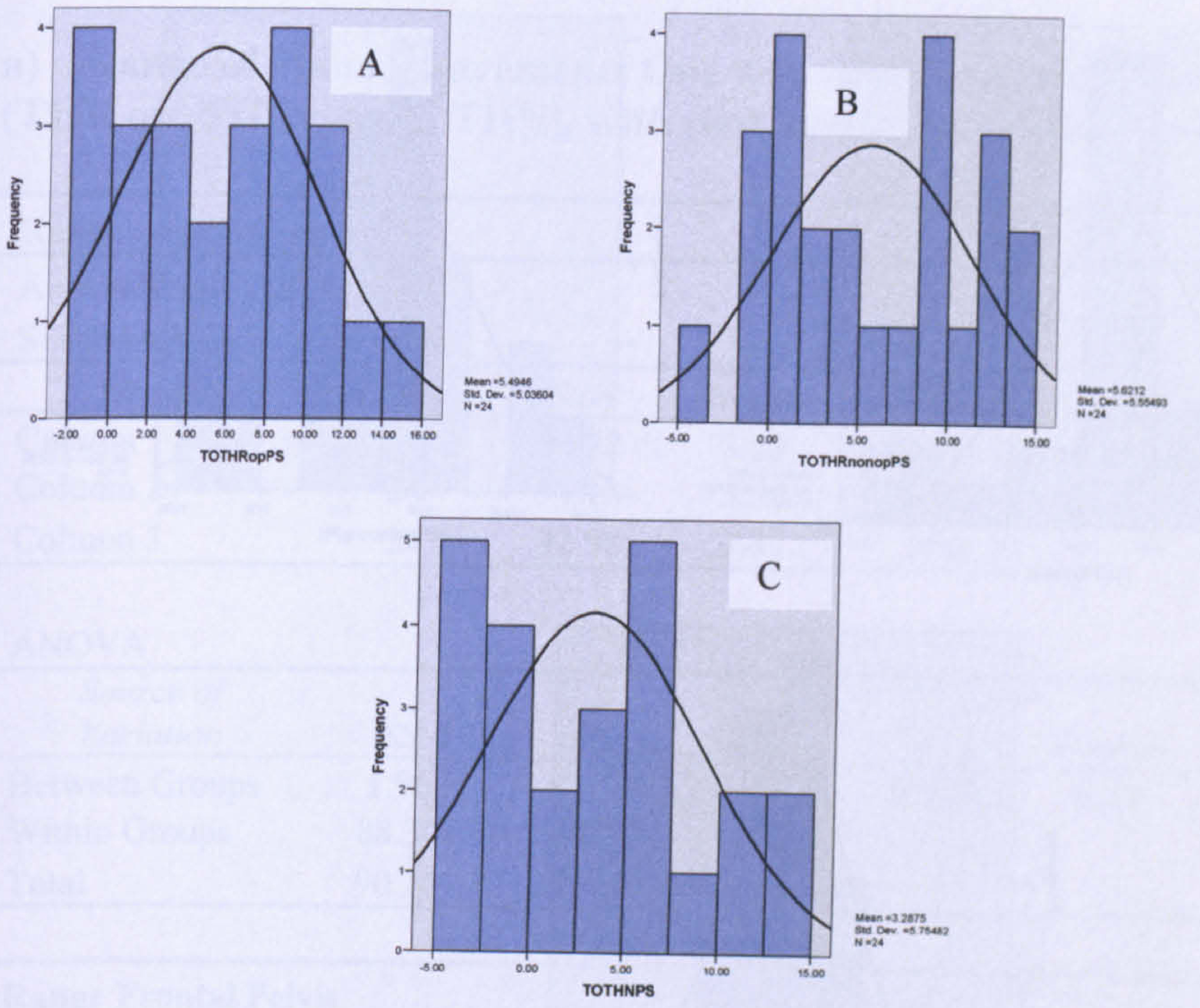
Sagittal plane lumbar spine motion at heel strike,
A: THR op, B: THR non op, C: THN



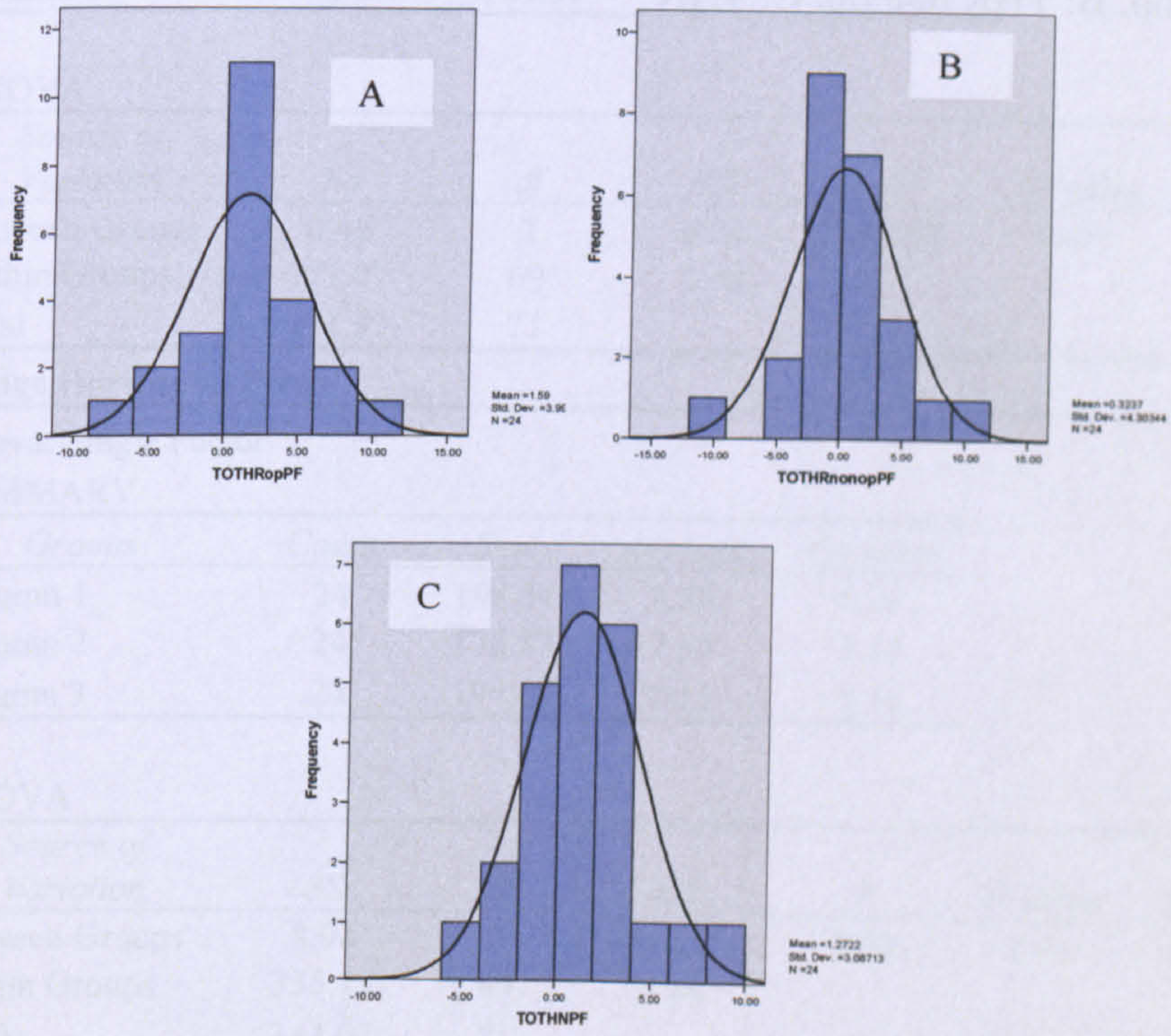
Frontal plane lumbar spine motion at heel strike,
A: THR op, B: THR non op, C: THN, A.



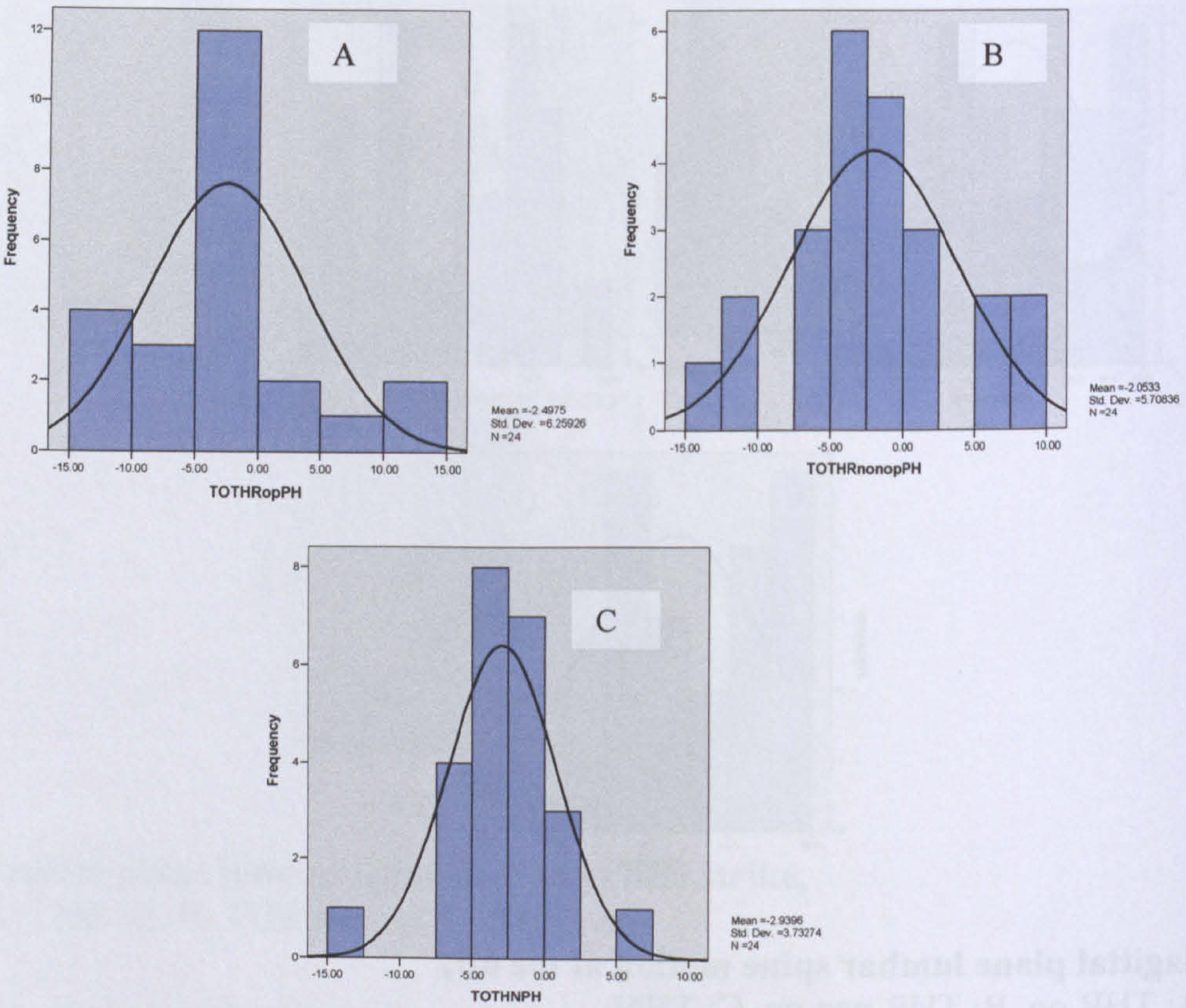
Horizontal plane lumbar spine motion at heel strike,
A: THR op, B: THR non op, C: THN



Sagittal plane lumbar spine motion at toe off,
A: THR op, B: THR non op, C: THN



Frontal plane lumbar spine motion at toe off,
A: THR op, B: THR non op, C: THN



Horizontal plane lumbar spine motion at toe off,
A: THR op, B: THR non op, C: THN

3) Statistical Analysis

a) Range of Planar movements One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Range Sagittal Pelvis

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	85.22	3.55	0.86
Column 2	24	94.13	3.92	1.43
Column 3	24	92.98	3.87	1.56

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.96	2	0.98	0.77	0.47	3.13
Within Groups	88.30	69	1.28			
Total	90.26	71				

Range Frontal Pelvis

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	111.18	4.63	2.66
Column 2	24	106.94	4.456	2.43
Column 3	24	107.31	4.47	2.35

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.46	2	0.23	0.093	0.91	3.13
Within Groups	171.07	69	2.48			
Total	171.53	71				

Range Horizontal Pelvis

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	198.34	8.26	6.29
Column 2	24	178.83	7.45	3.12
Column 3	24	194.62	8.11	5.16

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.94	2	4.47	0.92	0.40	3.13
Within Groups	335.13	69	4.86			
Total	344.07	71				

b) Position Data at Heel strike: One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Heel Strike Sagittal

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	148.74	6.19	27.63
Column 2	24	119.30	4.97	28.00
Column 3	24	89.48	3.73	28.78

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	73.16	2	36.58	1.30	0.28	3.13
Within Groups	1941.32	69	28.14			
Total	2014.47	71				

Heel Strike Frontal

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-8.91	-0.37	17.98
Column 2	24	30.51	1.27	12.59
Column 3	24	-11.05	-0.46	11.17

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	45.65	2	22.82	1.64	0.20	3.13
Within Groups	960.05	69	13.91			
Total	1005.70	71				

Heel Strike Horizontal

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-14.72	-0.61	38.80
Column 2	24	0.75	0.031	34.70
Column 3	24	16.08	0.67	17.18

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	19.77	2	9.88	0.33	0.72	3.13
Within Groups	2085.89	69	30.23			
Total	2105.66	71				

c) Position Data at Toe Off: One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Toe Off Sagittal

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	134.91	5.62	30.86
Column 2	24	131.87	5.49	25.36
Column 3	24	78.9	3.29	33.12

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	82.67	2	41.34	1.39	0.26	3.13
Within Groups	2054.75	69	29.78			
Total	2137.42	71				

Toe Off Frontal

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-7.77	-0.32	18.52
Column 2	24	-38.16	-1.59	15.98
Column 3	24	-30.53	-1.27	9.53

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	20.83	2	10.42	0.71	0.50	3.13
Within Groups	1012.61	69	14.68			
Total	1033.44	71				

Toe Off Horizontal

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-49.28	-2.05	32.59
Column 2	24	-59.94	-2.49	39.18
Column 3	24	-70.55	-2.94	13.93

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9.43	2	4.7126	0.17	0.85	3.13
Within Groups	1971.03	69	28.57			
Total	1980.46	71				

Appendix T: Biomechanical Lumbar Spine Movement

1) Raw Data (n = 24 per group (THR and THN)

a) Range of motion from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN
	6.18	6.18	6.12	5.67	2.67	6.93	4.16	2.56	4.07
	11.87	7.30	4.90	10.39	8.78	8.26	2.90	2.48	4.22
	9.82	10.77	3.62	5.11	6.48	7.33	1.64	1.15	4.62
	7.80	7.60	6.98	11.20	5.20	5.22	8.12	5.12	6.40
	11.68	11.46	4.15	6.61	5.21	6.42	4.10	4.62	4.88
	11.26	9.00	5.18	14.31	9.72	9.91	5.35	3.59	5.82
	12.50	12.07	6.24	7.31	12.36	9.40	7.63	4.06	5.77
	7.64	8.68	4.49	9.28	4.28	11.88	6.17	3.05	10.42
	8.70	11.20	6.40	7.27	9.09	8.59	3.35	4.74	5.59
	9.40	9.79	4.91	9.74	10.80	10.15	8.23	5.92	9.72
	9.37	10.77	5.08	6.62	7.48	7.52	1.64	2.15	6.40
	10.93	6.73	3.96	7.85	5.82	11.52	8.38	3.09	9.53
	8.17	5.73	6.32	7.05	4.85	8.50	4.22	7.92	10.05
	6.58	5.08	5.97	5.86	7.26	9.57	3.59	2.93	5.02
	8.84	9.15	7.01	8.83	5.01	7.17	1.64	2.61	3.94
	9.06	11.01	3.61	7.52	3.53	5.51	5.27	0.55	8.04
	7.34	9.10	5.53	7.80	6.63	6.07	8.38	3.79	9.95
	5.92	6.87	6.02	11.49	7.09	6.59	1.13	2.50	5.78
	8.42	7.82	4.33	6.01	5.86	7.45	6.63	3.42	4.56
	9.38	6.98	5.56	12.68	4.55	6.31	2.81	6.37	6.74
	5.10	10.10	3.65	8.98	5.63	8.14	5.21	4.79	7.20
	10.93	11.73	4.40	5.85	5.82	11.11	8.58	6.69	10.15
	9.43	8.40	4.37	4.39	4.16	8.77	3.42	2.49	5.94
	11.20	6.41	5.77	8.32	9.10	10.09	4.60	4.08	8.94
Mean	9.06	8.75	5.19	8.17	6.56	8.27	4.88	3.78	6.82
SD	2.00	2.08	1.06	2.48	2.39	1.88	2.41	1.76	2.20

b) Hip position at Heel Strike from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN
	2.12	2.12	2.66	1.32	-0.32	-1.07	1.03	1.03	1.95
	4.24	-4.00	0.99	0.13	-3.35	1.86	-1.60	-5.33	-3.04
	-4.35	4.76	-3.09	-2.46	0.24	-1.55	-2.35	-0.06	-1.26
	-0.90	-0.90	2.29	-2.12	-3.12	1.52	-0.57	-0.57	2.64
	4.81	5.79	2.85	-3.70	1.01	-0.83	2.86	-0.97	-1.60
	-1.10	-1.60	-0.23	1.56	-1.06	-1.67	1.09	-2.41	-2.52
	0.90	-1.50	2.24	-3.60	0.27	-0.80	-4.35	0.00	2.29
	-2.80	-2.87	4.47	2.16	0.55	-1.56	4.41	-3.90	-4.58
	-1.38	-7.80	-3.04	2.29	-2.85	1.43	2.58	-5.33	2.92
	-0.80	-1.78	1.82	3.59	-3.00	1.25	-1.60	-9.40	-3.61
	-4.35	4.76	2.29	-2.46	-0.24	1.31	-2.35	-0.06	2.64
	4.2	0.17	0.80	-0.5	0.90	-1.70	4.1	-0.29	7.33
	-0.40	-0.86	1.76	-3.44	-2.04	0.56	-1.26	1.78	2.52
	2.18	1.23	-2.22	-0.06	-2.72	-1.26	1.83	0.23	-4.01
	0.53	3.70	-2.18	-3.13	-1.14	-0.24	1.20	-1.03	-3.38
	-1.18	-1.24	4.64	2.01	-3.98	-2.93	2.86	0.52	-11.29
	2.22	8.08	2.69	1.50	-3.24	1.60	-3.09	0.57	2.69
	-1.78	-2.21	-1.27	2.18	1.06	1.79	-0.63	-3.21	1.78
	1.36	2.75	-1.79	1.78	-3.24	-3.27	-1.20	2.18	-3.09
	0.06	-2.18	-1.35	-1.95	1.18	-0.82	0.46	0.11	-0.11
	1.32	8.08	-0.64	-0.46	-4.44	-2.23	-0.97	0.57	-0.23
	4.2	0.17	4.64	-0.5	0.90	2.93	4.1	-0.29	-11.29
	-3.66	0.52	-4.07	-2.55	-3.24	-0.58	-4.35	-3.04	0.86
	-0.95	-2.23	2.80	2.01	-2.72	1.52	9.40	-5.96	10.52
Mean	0.19	0.54	0.71	-0.27	-1.44	-0.20	0.48	-1.45	-0.50
SD	2.67	3.85	2.61	2.28	1.89	1.71	3.20	2.82	4.90

c) Hip position at Toe Off from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN
	1.32	0.92	-0.8	-2.49	-2.99	-4.34	-3.32	-3.32	-2.52
	-0.29	5.1	-0.01	-3.29	-3.79	-5.99	-1.32	0.52	-2.18
	3.67	1.15	2.71	-4.32	-4.82	-6.32	1.95	-2.69	2.92
	-0.57	0.63	0.63	0.78	-1.28	-1.22	5.39	4.93	-2.75
	2.86	1.78	-6.44	-3.01	-3.51	-5.01	1.38	-2.98	1.6
	3.60	2.41	4.18	-4.67	-5.17	-5.67	-1.78	2.23	-0.52
	0.40	-0.29	-2.66	2.56	2.06	-0.56	5.27	-4.93	-4.28
	-1.38	0.11	-9.57	-5.27	-5.77	-6.27	-0.53	0.92	4.3
	2.57	-0.92	2.67	3.3	2.8	-1.8	-1.2	4.41	0.06
	1.94	-3.84	4.01	0.6	-0.3	-2.4	-3.68	-7.39	0.97
	2.80	0.23	-0.01	0.03	-0.47	-1.97	2.29	-2.75	-0.23
	-3.10	0.50	0.57	-0.72	-1.22	-2.72	5.9	-5.16	-2.86
	-3.38	-2.23	-8.40	0.89	0.39	-1.11	2.75	-3.72	-3.38
	1.40	-1.55	2.52	-5.81	-6.31	-7.81	-2.86	2.46	-0.63
	2.80	0.97	3.78	-4.95	-5.45	-6.95	1.6	-3.04	1.14
	5.70	-1.38	-9.05	-7.71	-7.21	-7.71	-0.17	1.03	2.41
	-6.30	3.04	1.83	1.08	-0.56	-0.94	-0.29	3.15	-4.18
	2.52	-0.01	1.97	1.02	-0.86	-1.94	-0.29	0.57	-3.73
	-5.44	-2.64	1.72	-4.5	-5	-6.5	-2.86	-2.23	3.15
	-5.00	-4.47	-1.07	3.18	2.68	-2	2.35	-4.7	-1.43
	0.11	3.22	-1.32	-2.38	-2.88	-4.38	2.92	3.84	2.23
	-1.80	0.10	-9.05	-7.51	-7.45	-6.51	3.6	-5.84	1.55
	2.46	2.58	-1.26	1.29	-0.79	-0.7	1.24	0.97	0.57
	3.32	4.47	-4.95	-6.21	-6.71	-8.15	-1.49	3.61	0.23
Mean	0.43	0.41	-1.17	-2.00	-2.69	-4.12	0.70	-0.84	-0.32
SD	3.21	2.40	4.43	3.43	3.13	2.59	2.79	3.63	2.50

d) Mean Sagittal plane lumbar spine moments through the Gait Cycle (°) (n=24)

	THR OP	THR Non OP	THN
0	1.00	-1.80	-0.80
2	1.80	-0.73	-0.80
4	2.60	0.34	-0.11
6	3.20	1.20	0.60
8	4.08	1.80	1.08
10	4.40	2.47	1.60
12	4.40	3.20	2.00
14	4.08	3.60	2.27
16	3.80	4.00	2.55
18	2.90	4.15	2.40
20	2.20	3.92	2.13
22	1.60	3.54	1.60
24	0.60	2.60	0.87
26	-0.46	1.25	0.40
28	-1.55	-0.20	-0.60
30	-2.60	-1.69	-1.31
32	-3.32	-3.32	-1.94
34	-3.91	-4.00	-2.50
36	-4.20	-4.60	-2.64
38	-3.74	-4.54	-2.64
40	-3.20	-4.54	-2.64
42	-2.65	-4.00	-2.36
44	-1.47	-3.09	-1.94
46	-0.88	-2.56	-1.45
48	0.00	-1.72	-0.80
50	1.05	-1.00	-0.46
52	1.89	-0.04	-0.11
54	3.00	0.95	0.45
56	3.55	1.40	1.08
58	4.08	2.00	1.64
60	4.20	2.71	2.00
62	4.00	3.20	2.27
64	3.66	3.64	2.34
66	2.64	3.90	2.06
68	2.34	3.64	1.80
70	1.66	3.31	0.73
72	0.45	3.05	-0.11
74	-0.54	2.40	-0.80
76	-1.52	1.20	-1.40
78	-2.13	-0.51	-2.00
80	-3.07	-1.80	-2.36
82	-3.66	-2.71	-2.40
84	-4.00	-3.40	-2.29
86	-4.60	-3.73	-2.20
88	-4.66	-3.90	-1.80
90	-4.20	-3.40	-1.40
92	-3.80	-3.00	-0.80
94	-3.20	-2.20	-0.68
96	-2.65	-1.53	-0.32
98	-1.52	0.20	0.10
100	-0.80	0.95	0.80

e) Mean Frontal plane lumbar spine moments through the Gait Cycle (°) (n=24)

	THR OP	THR Non OP	THN
0	-0.27	-1.44	-3.44
2	-1.25	-1.69	-2.66
4	-0.25	-1.87	-1.66
6	0.94	-0.94	-0.40
8	2.56	-0.72	0.63
10	3.60	0.69	1.69
12	4.63	1.25	2.64
14	5.31	2.56	3.15
16	5.69	3.00	3.29
18	5.94	3.50	3.24
20	6.13	3.44	2.84
22	5.75	3.31	2.32
24	5.31	3.00	1.98
26	4.63	2.63	1.80
28	4.00	2.13	1.92
30	3.12	1.00	2.15
32	2.46	0.94	2.32
34	2.30	0.50	2.52
36	1.93	0.00	2.84
38	1.66	0.31	3.29
40	1.71	0.40	3.81
42	2.09	0.69	4.24
44	2.40	0.63	4.41
46	2.63	0.88	4.41
48	2.36	0.31	4.07
50	1.88	-0.40	3.41
52	1.13	-0.44	2.23
54	0.40	-0.94	0.63
56	-0.32	-1.37	-0.77
58	-1.12	-2.40	-2.01
60	-1.50	-2.62	-2.84
62	-2.04	-3.06	-3.07
64	-2.00	-2.69	-2.95
66	-1.66	-1.87	-2.66
68	-0.96	-1.94	-2.35
70	-0.80	-0.72	-2.09
72	-0.16	-0.89	-1.75
74	0.40	-0.12	-1.75
76	0.63	0.00	-1.95
78	0.80	0.25	-2.21
80	1.00	0.88	-2.44
82	1.13	0.56	-2.66
84	1.00	0.56	-2.86
86	1.00	0.44	-3.12
88	0.63	0.00	-3.55
90	0.43	-1.20	-3.70
92	0.25	-0.40	-3.67
94	0.54	-0.56	-3.58
96	0.32	-0.19	-3.27
98	0.19	-0.48	-2.69
100	0.11	-0.57	-2.03

f) Mean Horizontal plane lumbar spine moments through the Gait Cycle (°) (n=24)

	THR OP	THR Non OP	THN
0	-0.83	-0.03	-2.64
2	-0.86	-0.17	-2.78
4	-1.03	-0.40	-2.86
6	-1.58	-0.89	-2.98
8	-2.00	-1.43	-2.69
10	-2.23	-1.86	-2.12
12	-2.29	-1.95	-1.49
14	-2.35	-1.92	-1.27
16	-2.32	-1.89	-1.06
18	-2.29	-1.66	-0.77
20	-2.15	-1.40	-0.60
22	-1.80	-0.89	-0.26
24	-1.32	-0.46	0.34
26	-0.95	-0.26	1.15
28	-0.72	-0.11	1.86
30	-0.54	0.11	2.55
32	-0.11	0.23	2.98
34	-0.03	0.26	3.24
36	0.00	0.23	3.29
38	-0.09	0.09	3.15
40	-0.32	-0.29	2.75
42	-0.49	-0.57	2.69
44	-0.83	-0.74	3.04
46	-0.89	-0.92	3.50
48	-0.77	-0.86	3.75
50	-0.43	-0.66	3.67
52	0.00	-0.26	3.84
54	0.60	0.29	3.61
56	1.40	1.12	2.89
58	1.91	1.72	2.32
60	2.33	1.83	1.95
62	2.50	1.73	1.80
64	2.53	1.58	1.55
66	2.44	1.58	1.20
68	2.29	1.46	0.80
70	2.09	1.32	0.32
72	1.72	1.06	-0.23
74	1.46	0.63	-1.03
76	1.23	0.32	-1.72
78	0.89	0.23	-2.44
80	0.49	0.03	-2.84
82	0.37	0.03	-2.95
84	0.32	0.03	-2.84
86	0.26	0.34	-2.58
88	0.32	0.73	-2.52
90	0.34	0.96	-2.32
92	0.29	1.05	-2.61
94	0.32	1.00	-2.75
96	0.23	0.95	-2.72
98	0.06	0.20	-2.84
100	-0.11	0.09	-2.72

g) Mean THN Lumbar Spine planar motion through the Gait Cycle (°) (n=24)

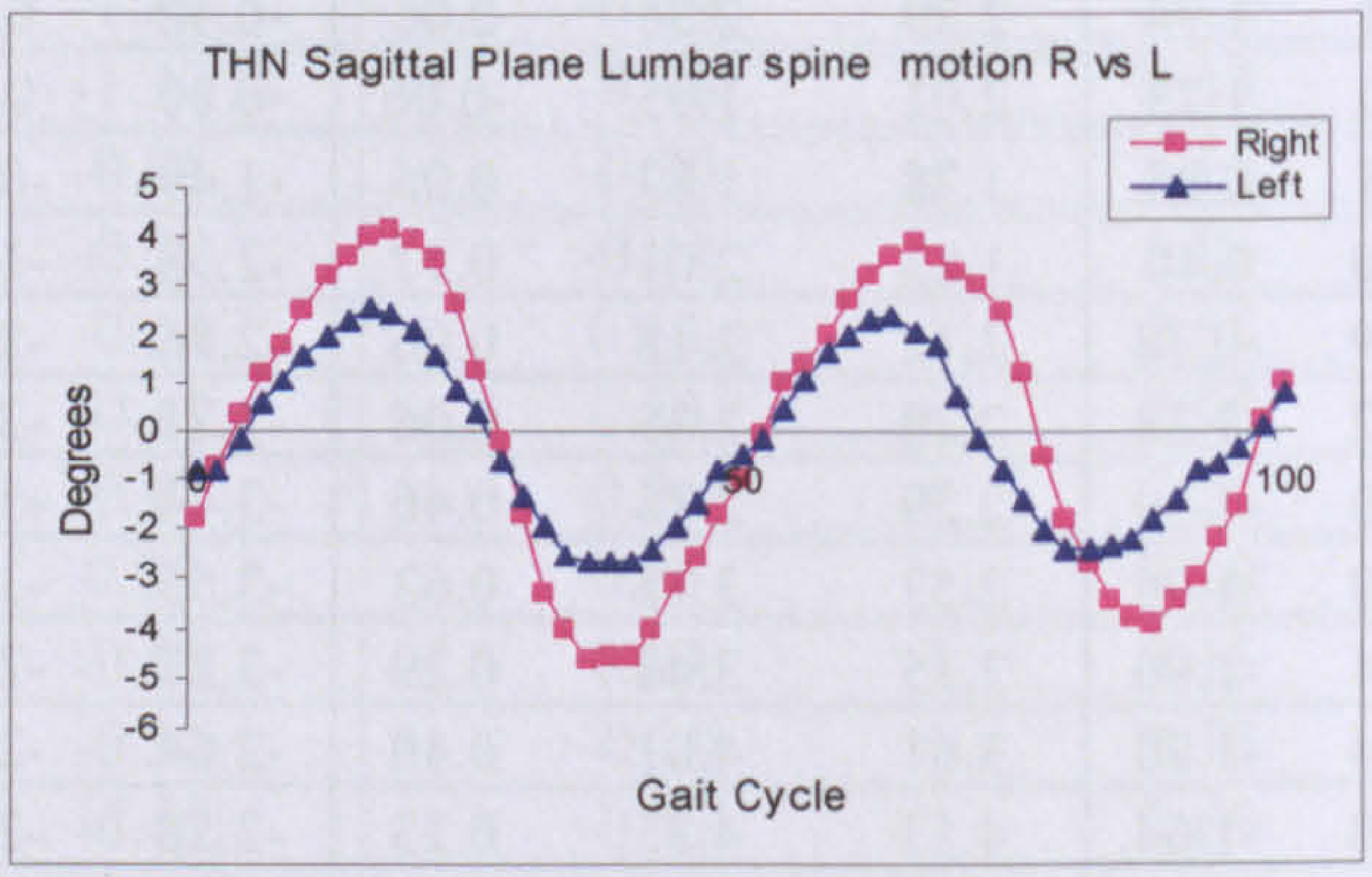
	Sagittal (°)			Frontal (°)			Horizontal (°)		
	Left	Right	Diff	Left	Right	Diff	Left	Right	Diff
0	-0.80	-1.80	-1.00	-3.38	-3.50	-0.11	2.69	2.58	-0.11
2	-0.80	-0.73	0.07	-2.75	-2.58	0.17	2.69	2.86	0.17
4	-0.11	0.34	0.45	-1.78	-1.55	0.23	2.69	3.04	0.34
6	0.60	1.20	0.60	-0.40	-0.40	0.00	2.75	3.21	0.46
8	1.08	1.80	0.72	0.52	0.74	0.23	2.41	2.98	0.57
10	1.60	2.47	0.87	1.43	1.95	0.52	1.95	2.29	0.34
12	2.00	3.20	1.20	2.35	2.92	0.57	1.43	1.55	0.11
14	2.27	3.60	1.33	2.86	3.44	0.57	1.20	0.92	-0.29
16	2.55	4.00	1.45	3.15	3.44	0.29	1.15	0.97	-0.17
18	2.40	4.15	1.75	3.15	3.32	0.17	0.86	1.15	0.29
20	2.13	3.92	1.79	2.81	2.86	0.06	-0.01	1.20	1.21
22	1.60	3.54	1.94	2.29	2.35	0.06	-0.40	0.92	1.32
24	0.87	2.60	1.73	2.01	1.95	-0.06	-0.80	0.11	0.92
26	0.40	1.25	0.85	1.78	1.83	0.06	-1.49	-0.80	0.69
28	-0.60	-0.20	0.40	1.83	2.01	0.17	-2.18	-1.55	0.63
30	-1.31	-1.69	-0.38	2.12	2.18	0.06	-2.86	-2.23	0.63
32	-1.94	-3.32	-1.38	2.29	2.35	0.06	-3.21	-2.86	0.35
34	-2.50	-4.00	-1.50	2.29	2.75	0.46	-3.44	-3.17	0.27
36	-2.64	-4.60	-1.96	2.52	3.15	0.63	-3.55	-3.43	0.12
38	-2.64	-4.54	-1.90	3.15	3.44	0.29	-3.27	-2.97	0.30
40	-2.64	-4.54	-1.90	3.61	4.01	0.40	-2.64	-2.35	0.29
42	-2.36	-4.00	-1.64	4.13	4.35	0.23	-2.58	-2.14	0.44
44	-1.94	-3.09	-1.15	4.30	4.53	0.23	-2.98	-2.20	0.78
46	-1.45	-2.56	-1.11	4.35	4.47	0.11	-3.27	-2.50	0.77
48	-0.80	-1.72	-0.92	3.95	4.18	0.23	-3.38	-2.97	0.41
50	-0.46	-1.00	-0.54	2.98	3.84	0.86	-3.32	-3.40	-0.08
52	-0.11	-0.04	0.07	1.60	2.86	1.26	-3.61	-3.48	0.13
54	0.45	0.95	0.50	0.01	1.26	1.25	-3.32	-3.33	-0.01
56	1.08	1.40	0.32	-1.26	-0.29	0.97	-2.58	-2.86	-0.28
58	1.64	2.00	0.36	-2.35	-1.66	0.69	-2.06	-2.58	-0.52
60	2.00	2.71	0.71	-2.92	-2.75	0.17	-1.95	-1.95	0.00
62	2.27	3.20	0.93	-2.75	-3.38	-0.63	-2.06	-1.55	0.52
64	2.34	3.64	1.30	-2.41	-3.50	-1.09	-1.78	-1.32	0.46
66	2.06	3.90	1.84	-1.95	-3.38	-1.43	-1.26	-1.15	0.11
68	1.80	3.64	1.84	-1.66	-3.04	-1.38	-0.74	-0.86	-0.11
70	0.73	3.31	2.58	-1.55	-2.64	-1.09	-0.11	-0.52	-0.40
72	-0.11	3.05	3.16	-1.26	-2.23	-0.97	0.46	-0.01	-0.46
74	-0.80	2.40	3.20	-1.38	-2.12	-0.74	1.20	0.86	-0.34
76	-1.40	1.20	2.60	-1.60	-2.29	-0.69	2.01	1.43	-0.57
78	-2.00	-0.51	1.49	-1.83	-2.58	-0.74	2.64	2.23	-0.40
80	-2.36	-1.80	0.56	-2.12	-2.75	-0.63	3.04	2.64	-0.40
82	-2.40	-2.71	-0.31	-2.46	-2.86	-0.40	3.27	2.64	-0.63
84	-2.29	-3.40	-1.11	-2.81	-2.92	-0.11	3.15	2.52	-0.63
86	-2.20	-3.73	-1.53	-3.09	-3.15	-0.06	2.86	2.29	-0.57
88	-1.80	-3.90	-2.10	-3.61	-3.50	0.11	3.04	1.60	-1.44
90	-1.40	-3.40	-2.00	-3.84	-3.55	0.29	2.92	1.32	-1.60
92	-0.80	-3.00	-2.20	-3.67	-3.67	0.00	2.86	0.90	-1.96
94	-0.68	-2.20	-1.52	-3.50	-3.67	-0.17	2.92	0.65	-2.27
96	-0.32	-1.53	-1.21	-3.21	-3.32	-0.11	2.81	0.60	-2.21
98	0.10	0.20	0.10	-2.69	-2.69	0.00	2.64	0.49	-2.15
100	0.80	0.95	0.15	-2.69	-1.38	1.32	2.64	0.54	-2.10

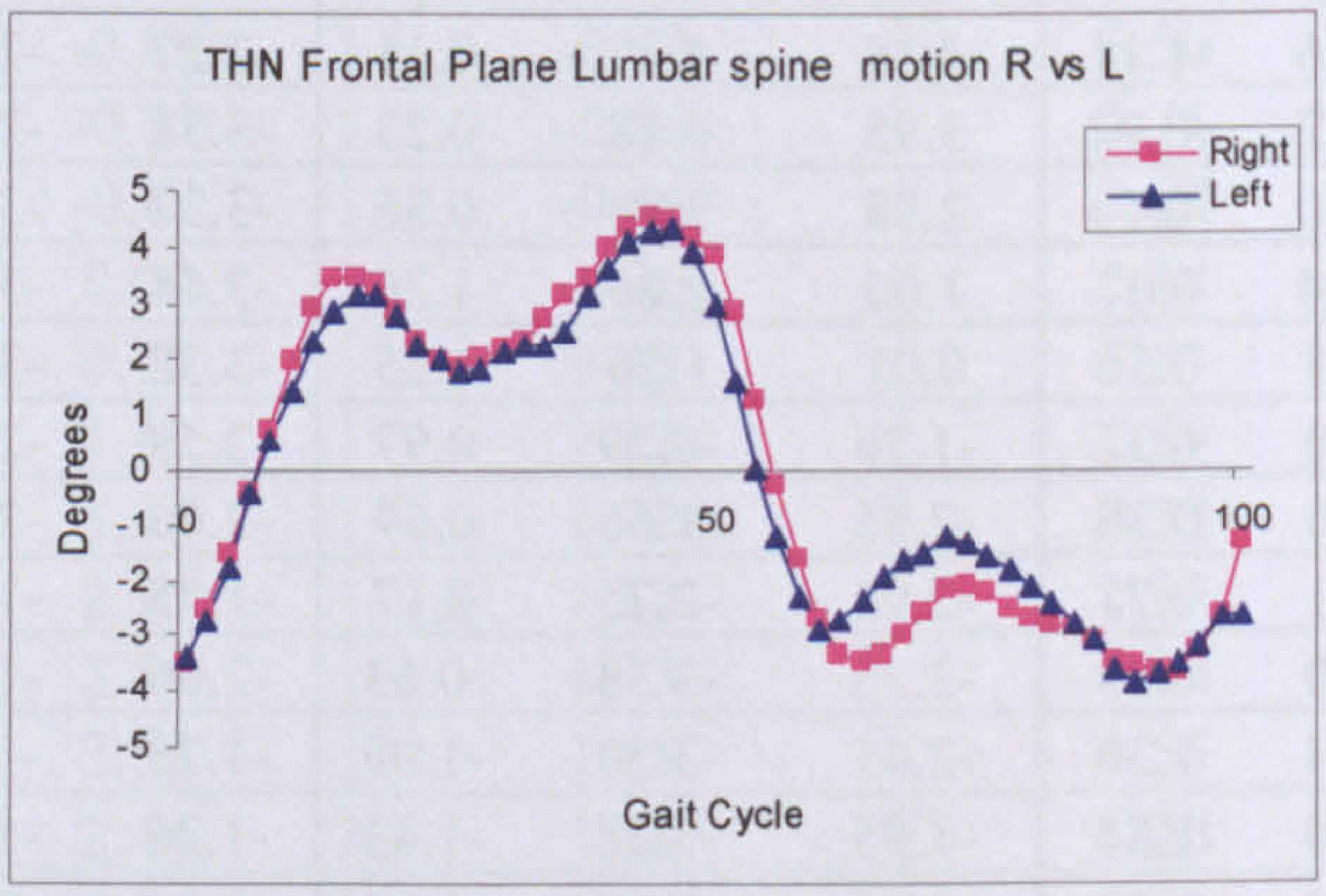
Lumbar spine movement, comparison of left and right sided data during walking

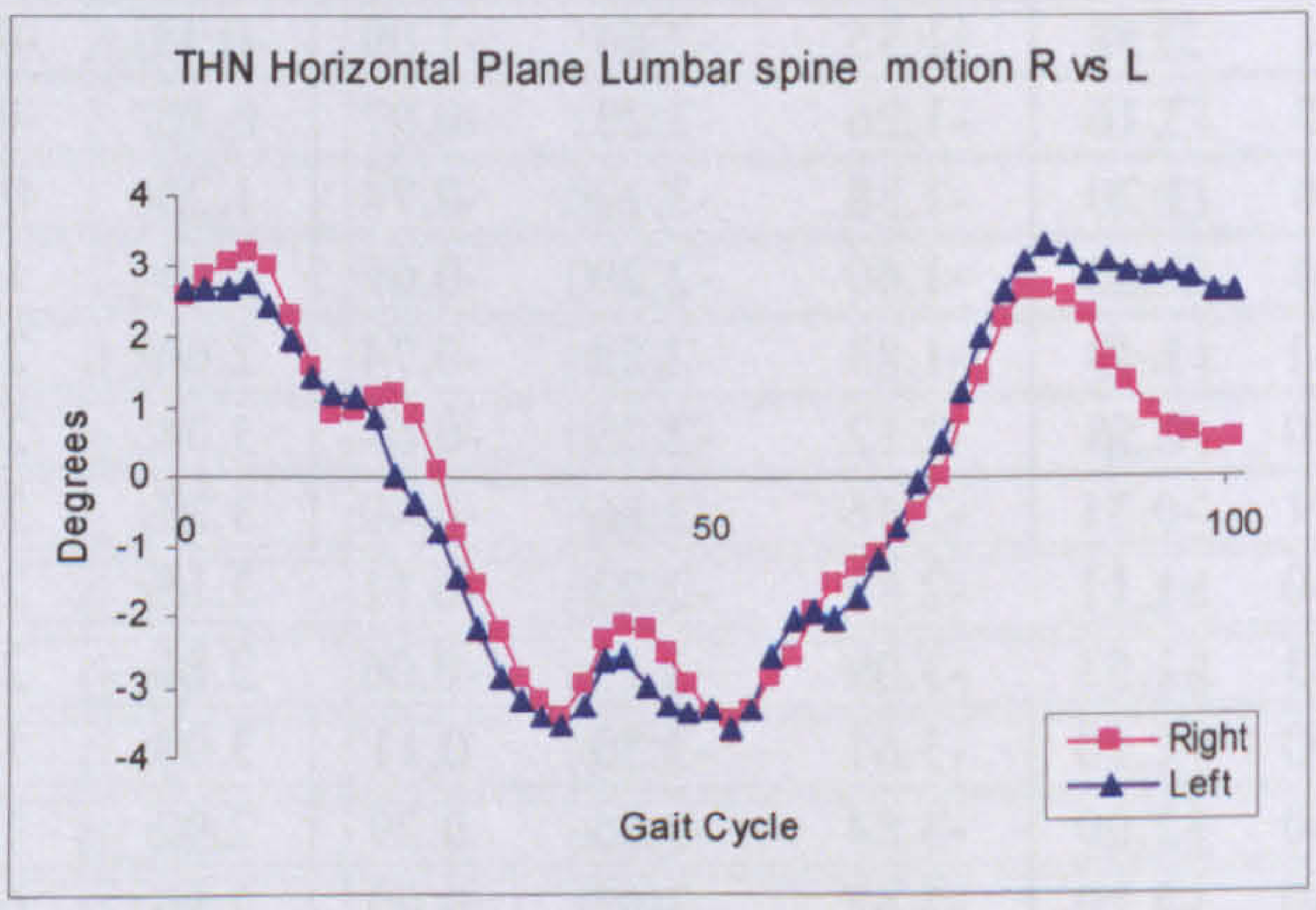
Two sample t-test between THN right and left data sets

	t value	p value
Sagittal	-0.401	0.69
Frontal	-0.079	0.94
Horizontal	0.300	0.77

No significant difference between right and left data sets for Lumbar spine data for each plane, tested by two sample t-test, significance set at p≤0.05







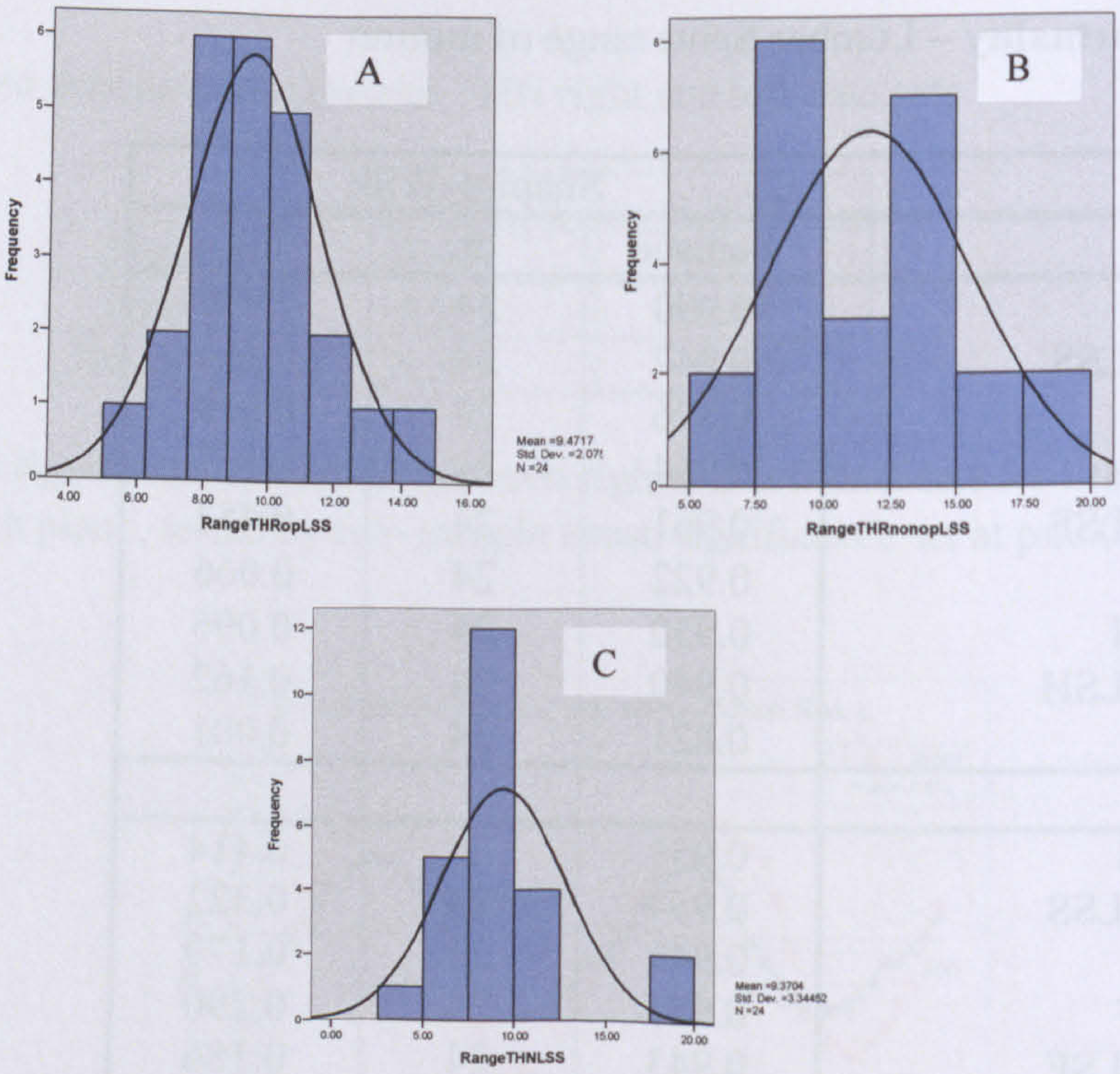
2) Test for Normal Distribution

a) Tests of Normality – Lumbar Spine range of motion

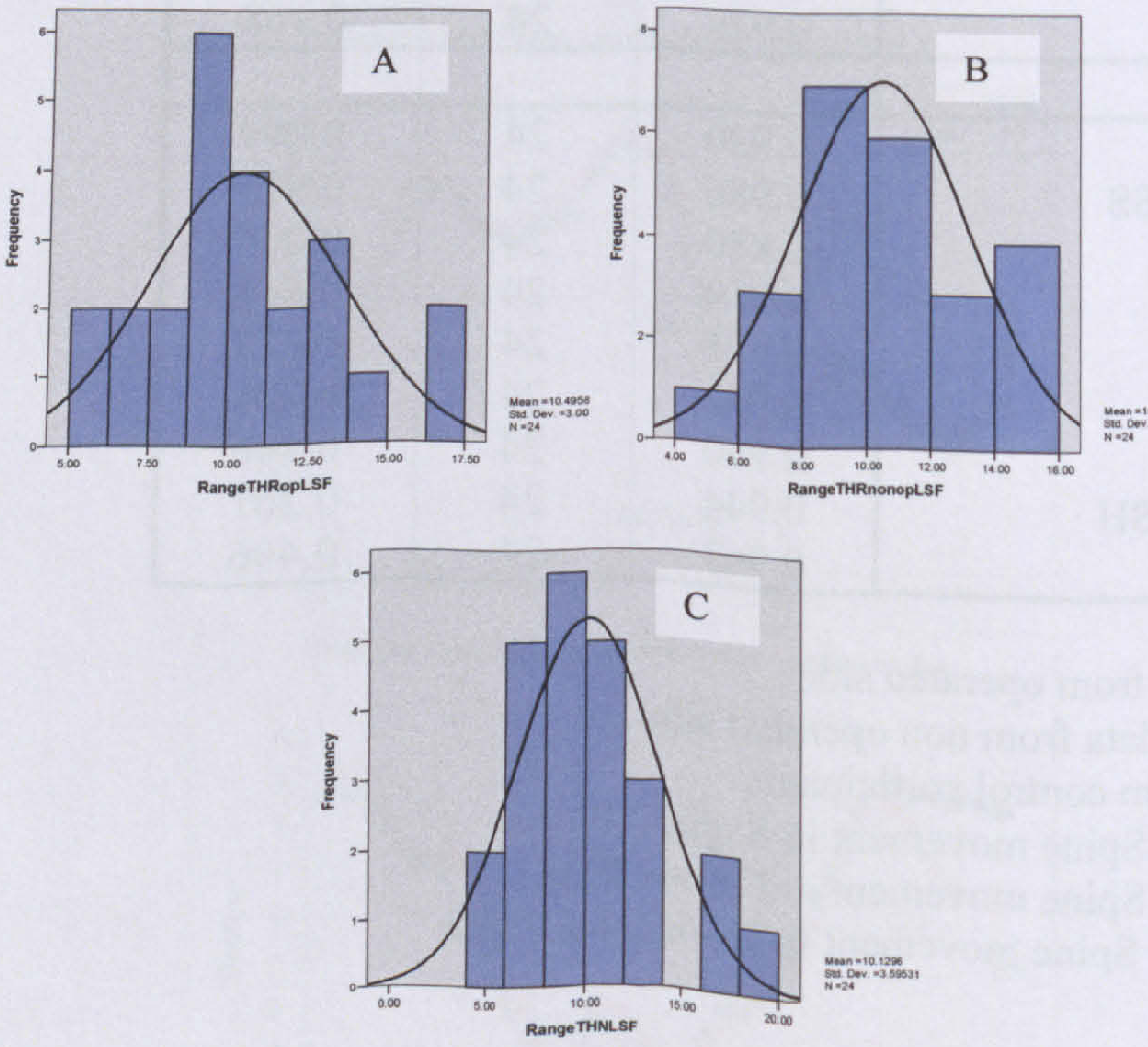
	Shapiro-Wilk		
Range	Statistic	df	Sig.
THR op LSS	0.990	24	0.996
THR nonop LSS	0.947	24	0.234
THN LSS	0.896	24	0.018
THR op LSF	0.964	24	0.527
THR nonop LSF	0.961	24	0.457
THN LSF	0.922	24	0.066
THR op LSH	0.930	24	0.096
THR nonop LSH	0.940	24	0.162
THN LSH	0.821	24	0.001
Heel Strike			
THR op LSS	0.959	24	0.414
THR nonop LSS	0.954	24	0.322
THN LSS	0.941	24	0.170
THR op LSF	0.951	24	0.290
THR nonop LSF	0.943	24	0.186
THN LSF	0.960	24	0.437
THR op LSH	0.949	24	0.259
THR nonop LSH	0.876	24	0.007
THN LSH	0.939	24	0.158
Toe Off			
THR op LSS	0.930	24	0.099
THR nonop LSS	0.986	24	0.973
THN LSS	0.880	24	0.008
THN LSS	0.969	24	0.643
THR op LSF	0.901	24	0.023
THN LSF	0.972	24	0.706
THR op LSH	0.960	24	0.446
THR nonop LSH	0.944	24	0.201
THN LSH	0.963	24	0.496

THR op – data from operated side
THR non op - data from non operated side
THN - data from control participants
LSS – Lumbar Spine movement in Sagittal Plane
LSF – Lumbar Spine movement in Frontal Plane
LSH – Lumbar Spine movement in Horizontal Plane

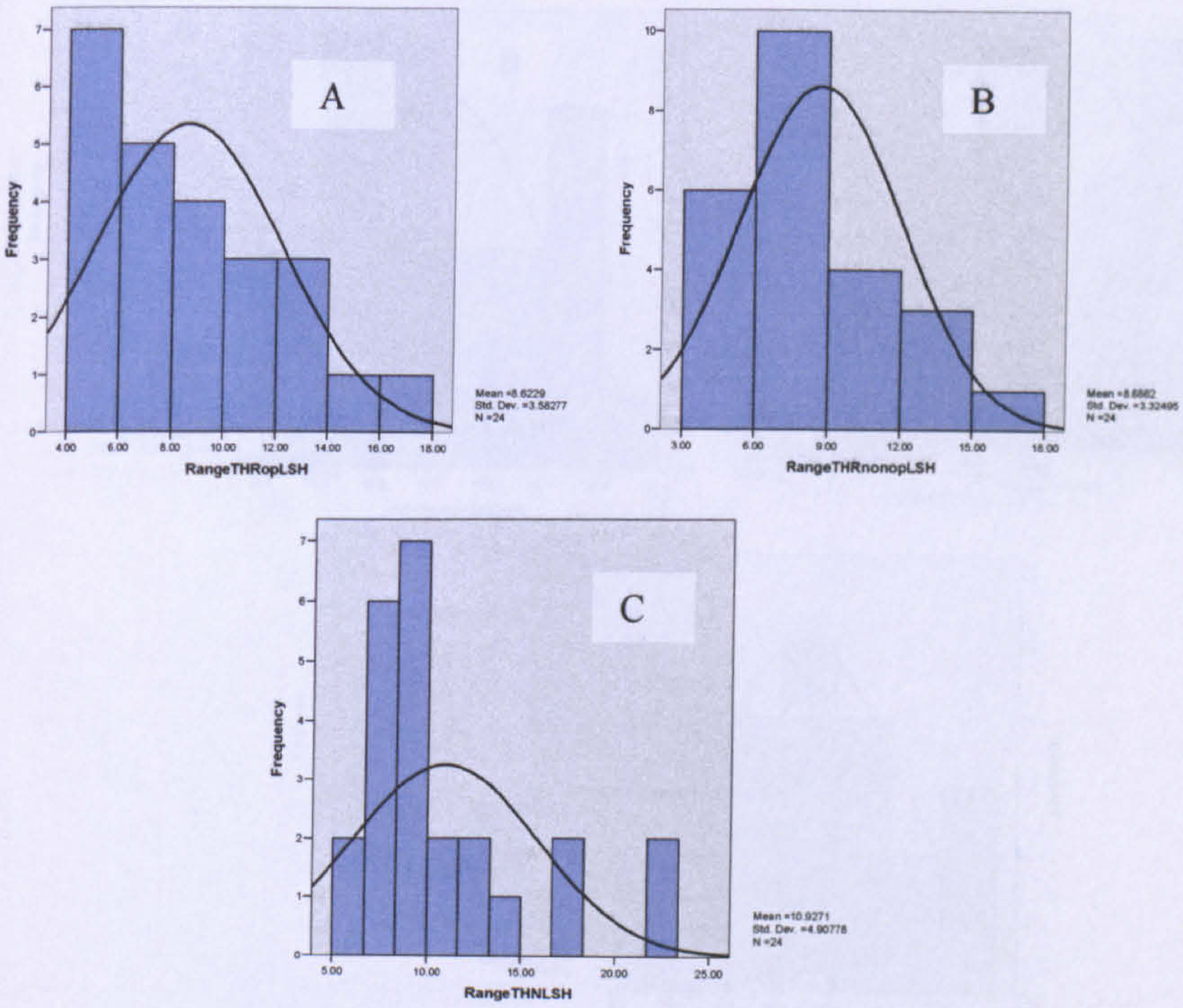
b) Normal Distribution plots



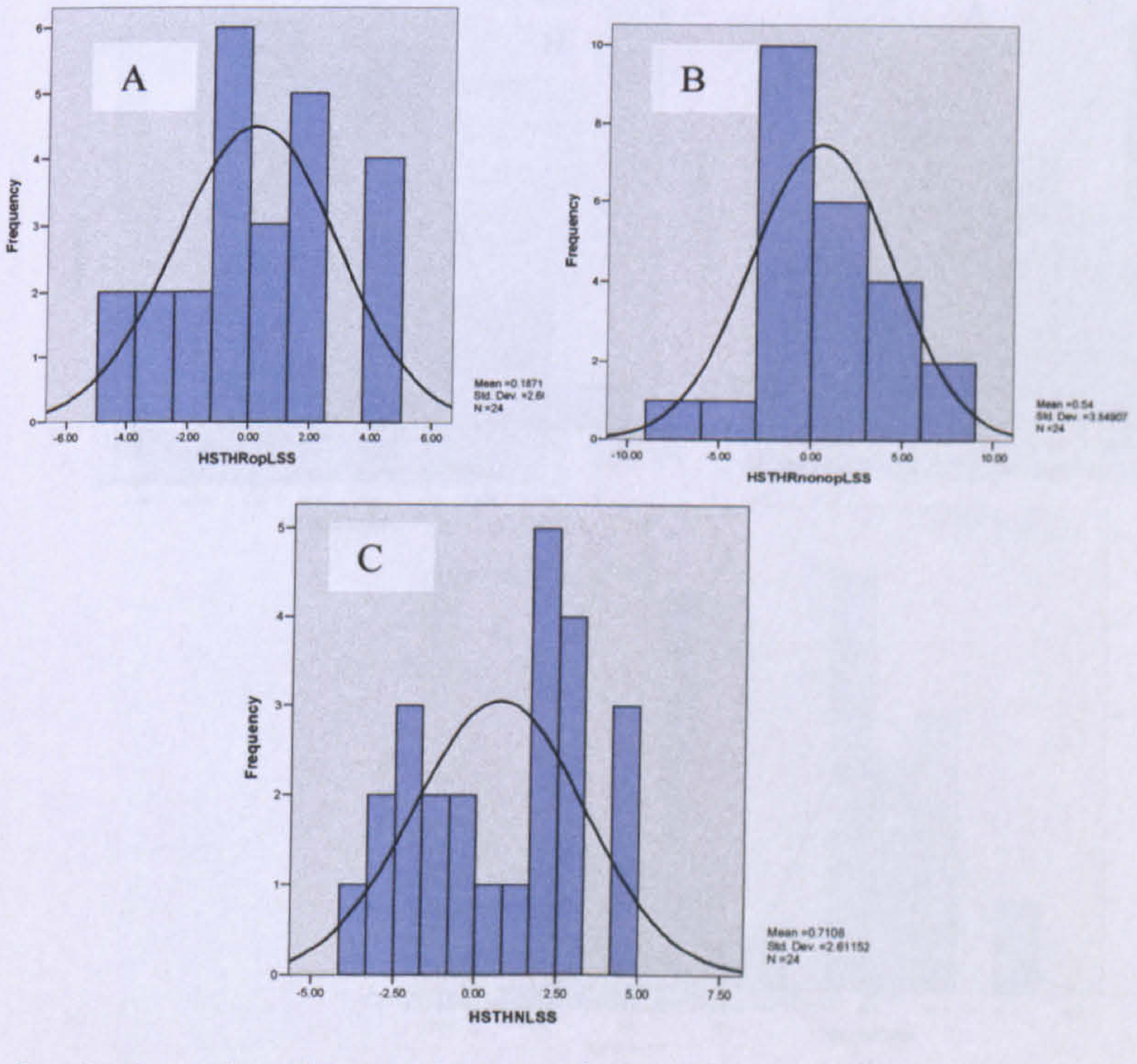
Range of sagittal plane lumbar spine motion,
A: THR op, B: THR non op, C: THN



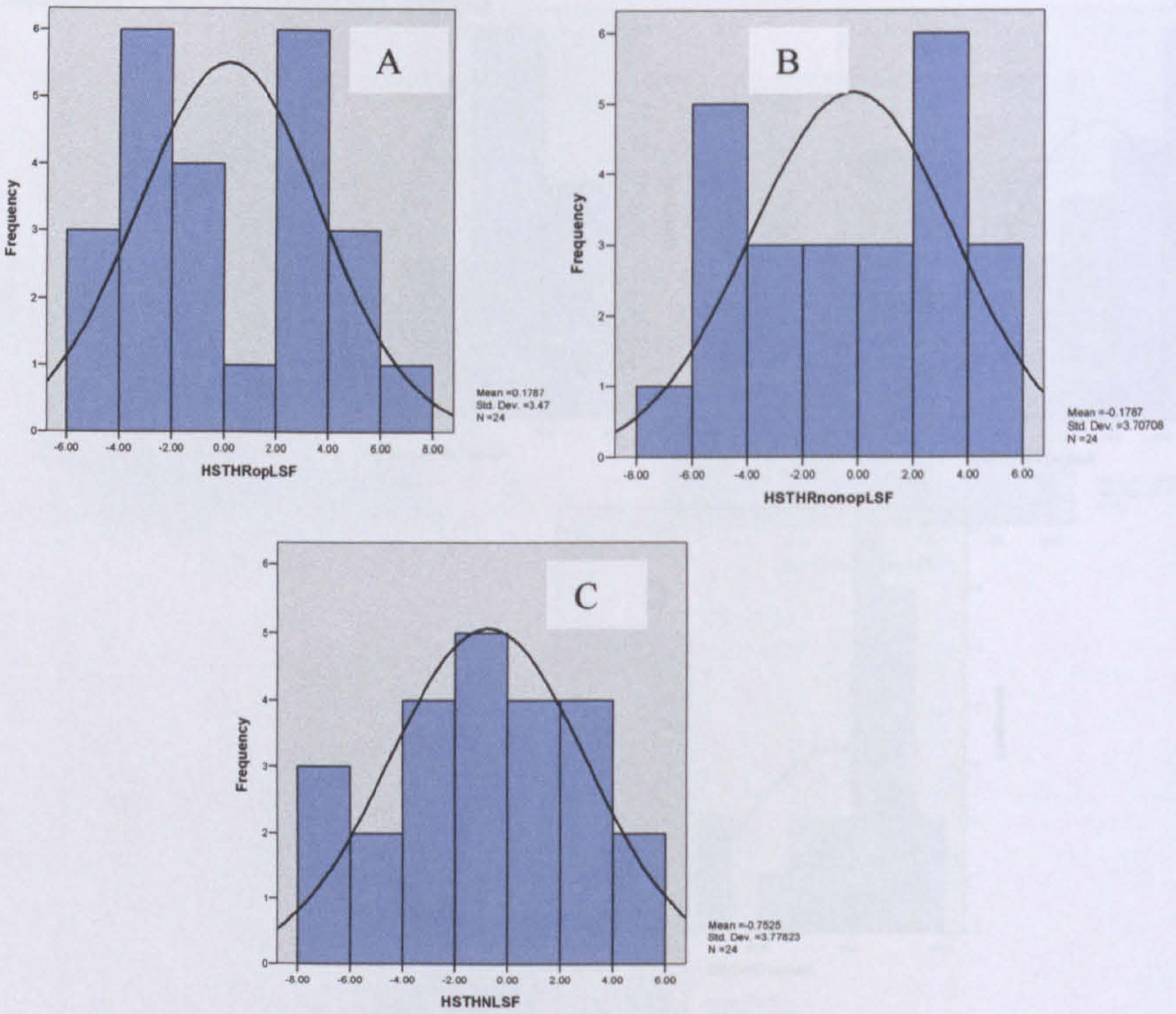
Range of frontal plane lumbar spine motion,
A: THR op, B: THR non op, C: THN



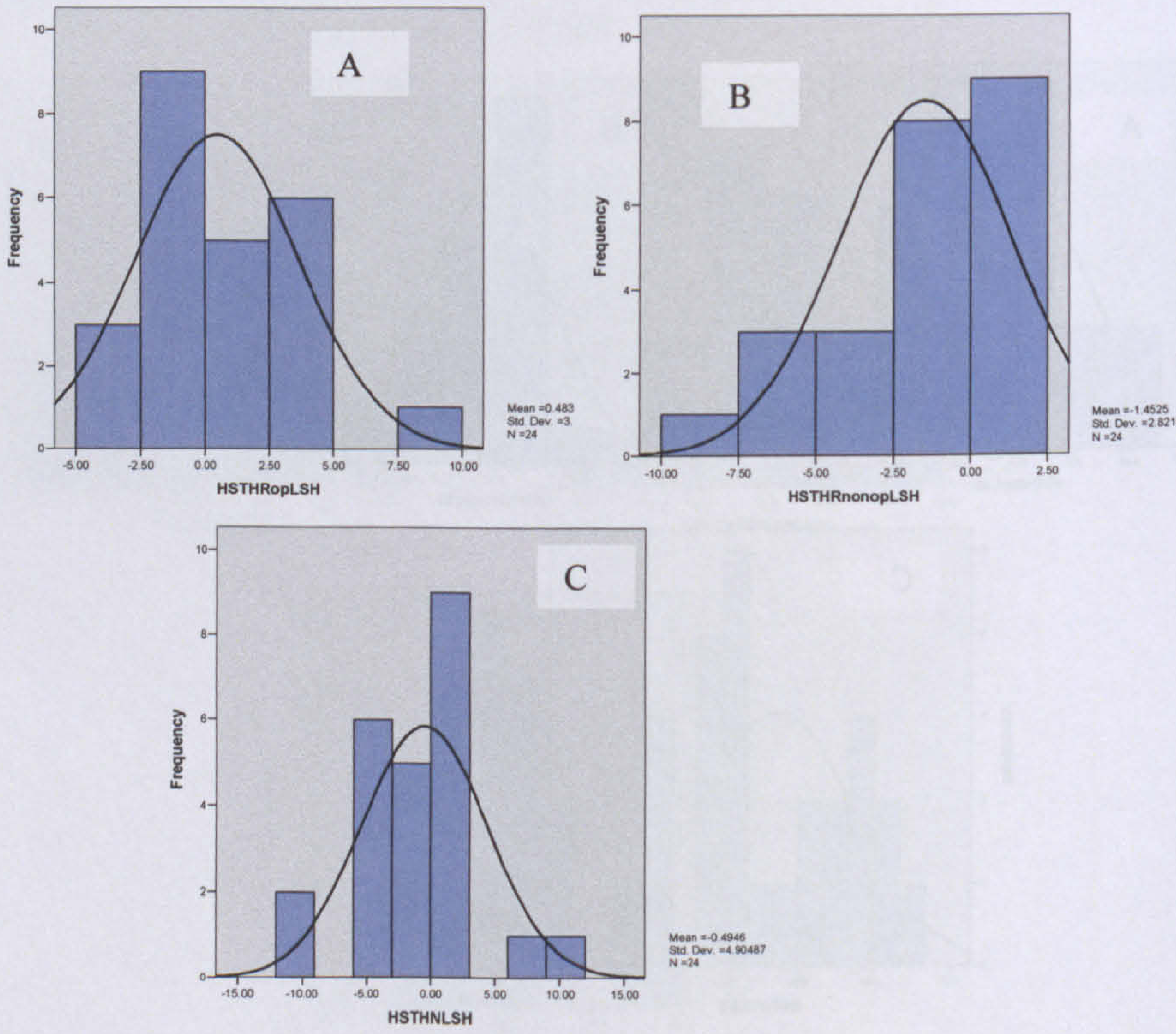
Range of horizontal plane lumbar spine motion,
A: THR op, B: THR non op, C: THN



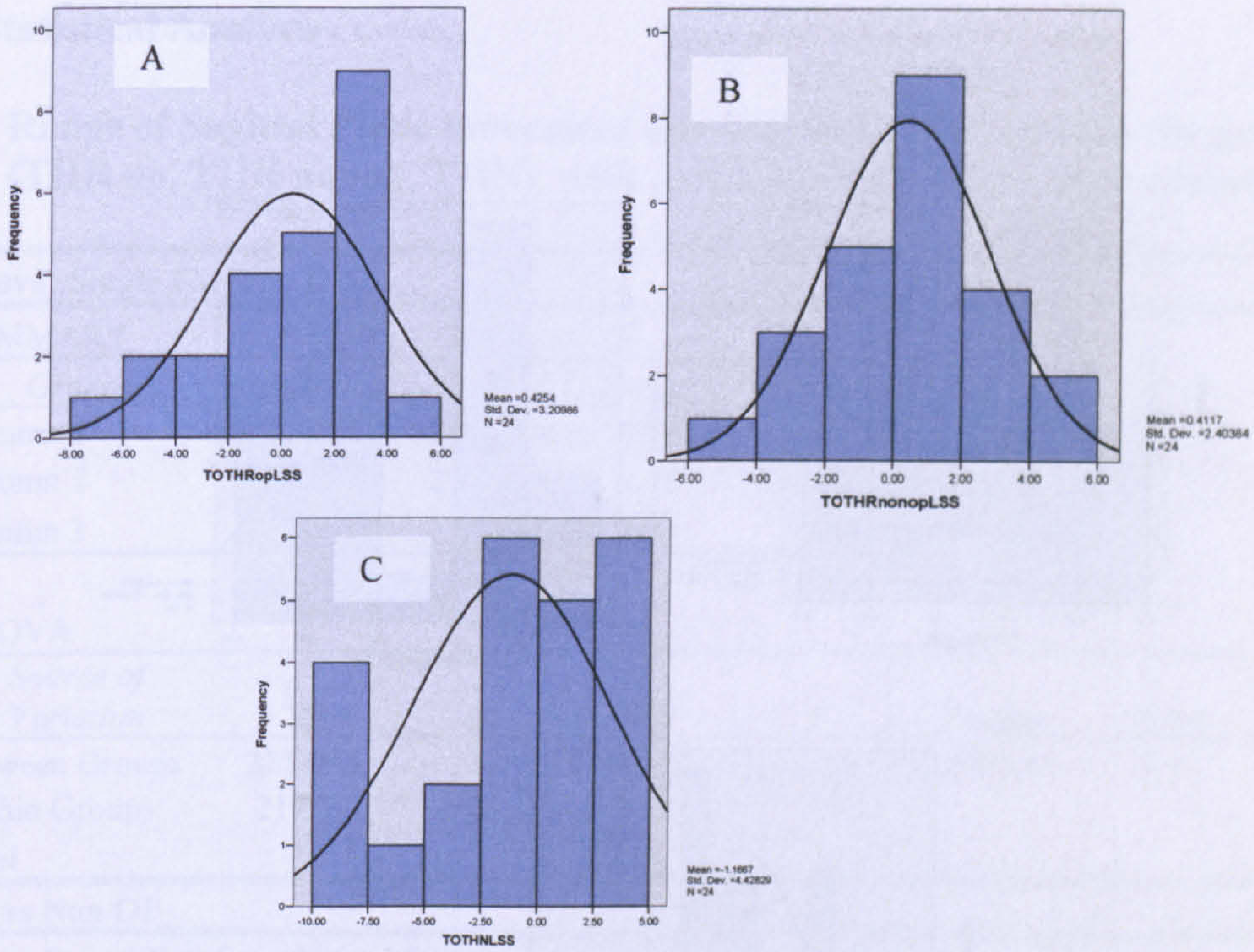
Sagittal plane lumbar spine motion at heel strike,
A: THR op, B: THR non op, C: THN



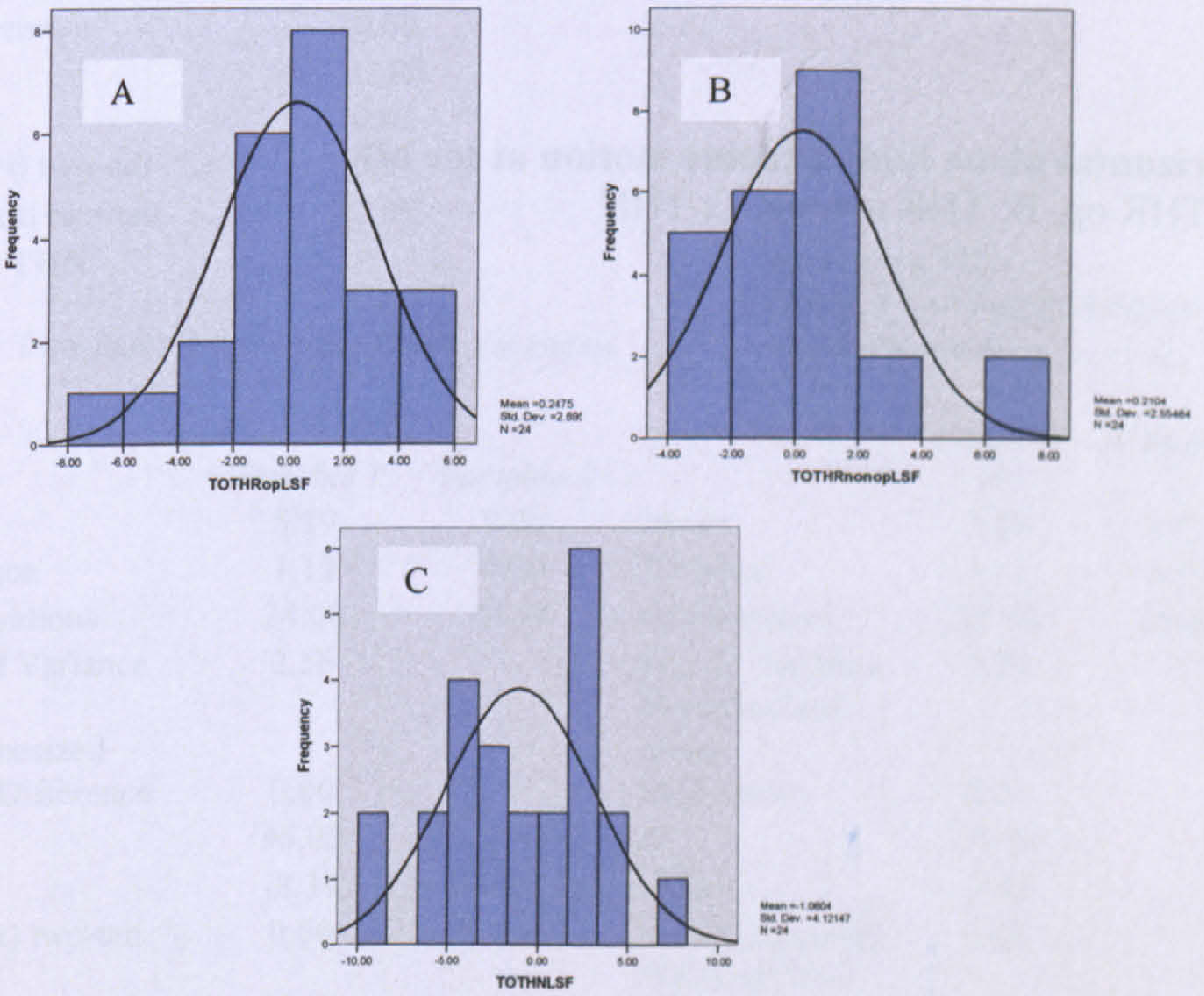
Frontal plane lumbar spine motion at heel strike,
A: THR op, B: THR non op, C: THN



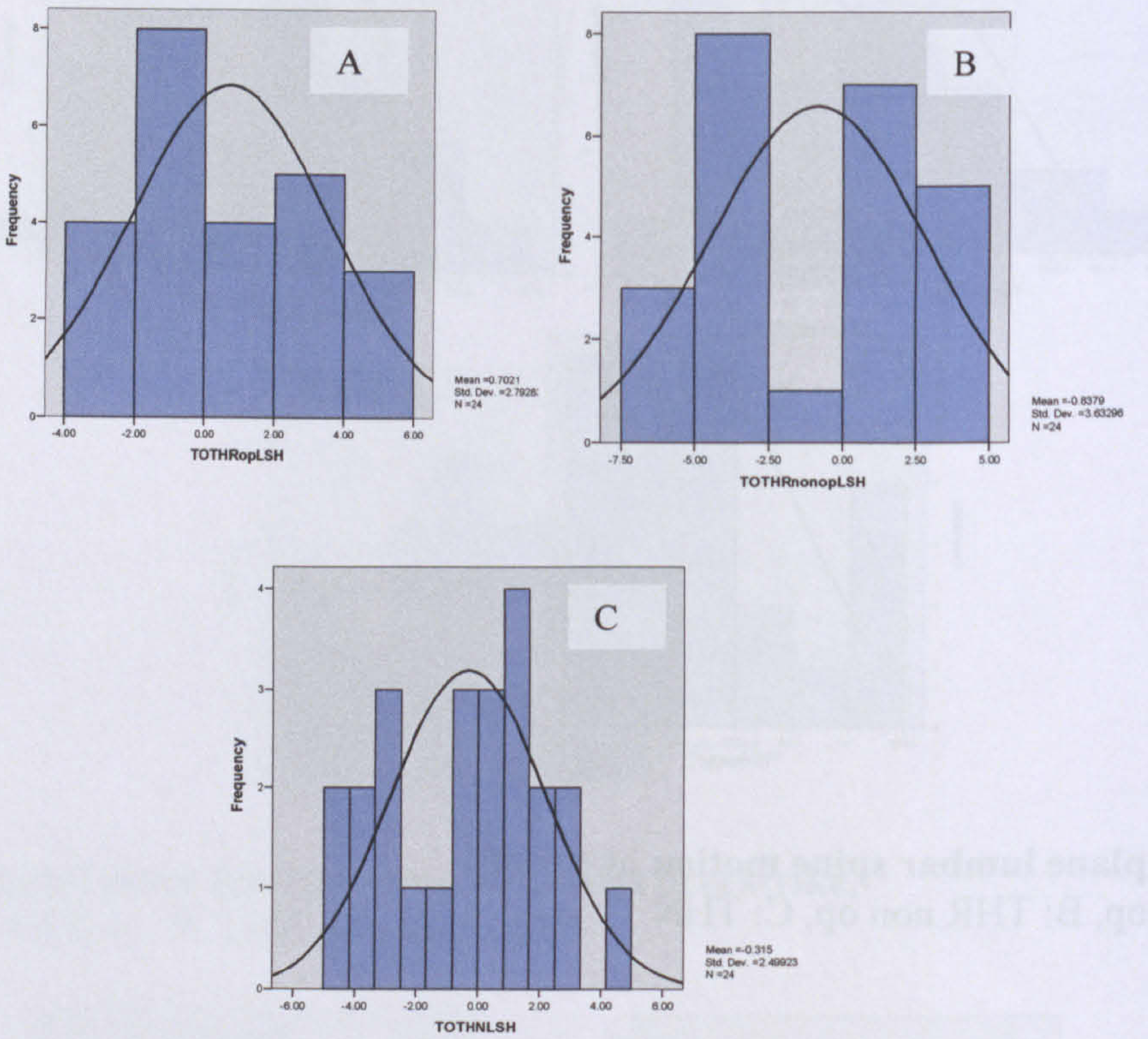
Horizontal plane lumbar spine motion at heel strike,
A: THR op, B: THR non op, C: THN



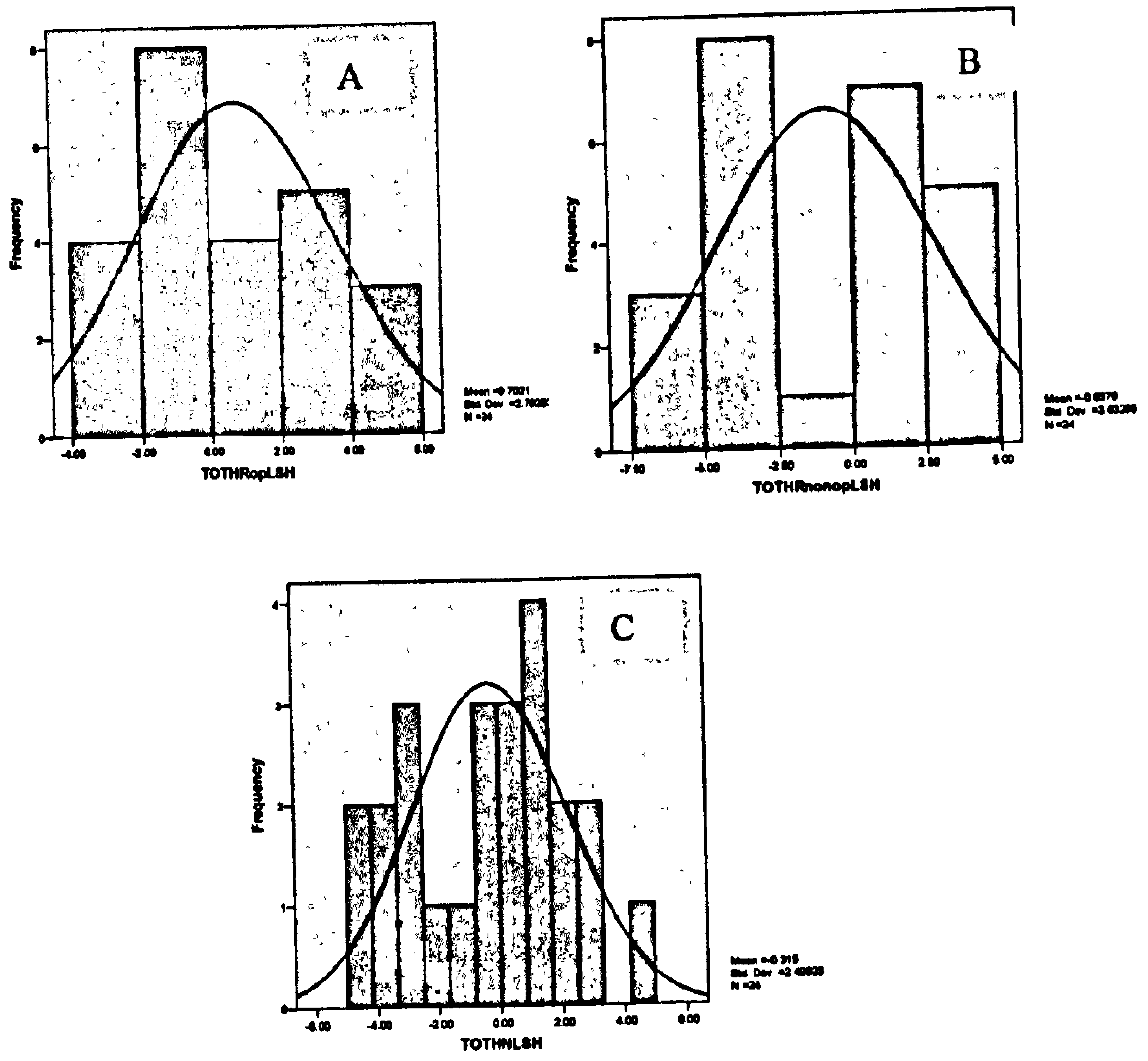
Sagittal plane lumbar spine motion at toe off,
A: THR op, B: THR non op, C: THN



Frontal plane lumbar spine motion at toe off,
A: THR op, B: THR non op, C: THN



Horizontal plane lumbar spine motion at toe off,
A: THR op, B: THR non op, C: THN



Horizontal plane lumbar spine motion at toe off,
A: THR op, B: THR non op, C: THN

b) Range of Frontal Plane movement One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	196.14	8.17	6.16
Column 2	24	157.38	6.56	5.73
Column 3	24	198.41	8.27	3.55

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	44.32	2.00	22.16	4.31	0.017	3.13
Within Groups	354.90	69.00	5.14			
Total	399.22	71.00				

OP vs Non OP

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	8.17	6.56
Variance	6.16	5.73
Observations	24.00	24.00
Pearson Correlation	0.25	
Hypothesized Mean Difference	0.00	
df	23.00	
t Stat	2.65	
P(T<=t) two-tail	0.014	
t Critical two-tail	2.07	

OP vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	8.27	8.17
Variance	3.55	6.16
Observations	24.00	24.00
Pooled Variance	4.85	
Hypothesized Mean Difference	0.00	
df	46.00	
t Stat	0.15	
P(T<=t) two-tail	0.88	
t Critical two-tail	2.01	

Non op vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	8.27	6.56
Variance	3.55	5.73
Observations	24.00	24.00
Pooled Variance	4.64	
Hypothesized Mean Difference	0.00	
df	46.00	
t Stat	2.75	
P(T<=t) two-tail	0.01	
t Critical two-tail	2.01	

c) Range of Horizontal Plane movement One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	117.15	4.88	5.84
Column 2	24	90.67	3.78	3.10
Column 3	24	163.75	6.82	4.85

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	114.08	2	57.04	12.41	0.00	3.13
Within Groups	317.04	69	4.59			
Total	431.11	71				

OP vs Non OP

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	4.88	3.78
Variance	5.84	3.10
Observations	24.00	24.00
Pearson Correlation	0.37	
Hypothesized Mean Difference	0.00	
df	23.00	
t Stat	2.25	
P(T<=t) two-tail	0.03	
t Critical two-tail	2.07	

Op vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	6.82	4.88
Variance	4.85	5.84
Observations	24.00	24.00
Pooled Variance	5.34	
Hypothesized Mean Difference	0.00	
df	46.00	
t Stat	2.91	
P(T<=t) two-tail	0.006	
t Critical two-tail	2.01	

Non op vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	6.82	3.78
Variance	4.85	3.10
Observations	24.00	24.00
Pooled Variance	3.97	
Hypothesized Mean Difference	0.00	
df	46.00	
t Stat	5.29	
P(T<=t) two-tail	0.0000	
t Critical two-tail	2.01	

d) Lumbar Spine position data at Heel Strike One way ANOVA between the groups (THR op, THR nonop, THN)

Sagittal Plane Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	4.47	0.19	7.11
Column 2	24	12.94	0.54	14.81
Column 3	24	17.08	0.71	6.82

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.44	2	1.72	0.18	0.84	3.13
Within Groups	660.88	69	9.58			
Total	664.32	71				

Frontal Plane Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-6.43	-0.27	5.19
Column 2	24	-34.60	-1.44	3.58
Column 3	24	-4.74	-0.19	2.92

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	23.45	2	11.73	3.01	0.056	3.13
Within Groups	268.79	69	3.89			
Total	292.25	71				

Horizontal Plane Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	11.63	0.49	10.21
Column 2	24	-34.84	-1.45	7.96
Column 3	24	-11.88	-0.49	24.06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	44.99	2	22.49	1.59	0.21	3.13
Within Groups	971.17	69	14.0745			
Total	1016.16	71				

e) Lumbar Spine position data at Toe off One way ANOVA between the groups (THR op, THR nonop, THN)

Sagittal Plane Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	10.21	0.43	10.30
Column 2	24	9.88	0.41	5.78
Column 3	24	-28.0005	-1.17	19.61

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	40.201	2	20.11	1.69	0.19	3.13
Within Groups	820.90	69	11.89			
Total	861.11	71				

Frontal Plane Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-48.11	-2.01	11.75
Column 2	24	-64.61	-2.69	9.77
Column 3	24	-98.97	-4.12	6.72

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	56.11	2	28.05	2.98	0.057	3.13
Within Groups	649.49	69	9.41			
Total	705.60	71				

Horizontal Plane Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	16.85	0.70	7.79
Column 2	24	-20.11	-0.84	13.19
Column 3	24	-7.56	-0.32	6.25

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	29.44	2	14.72	1.62	0.21	3.13
Within Groups	626.62	69	9.08			
Total	656.06	71				

Appendix U Mean angle-angle diagrams per group and plane

Key for all figures:

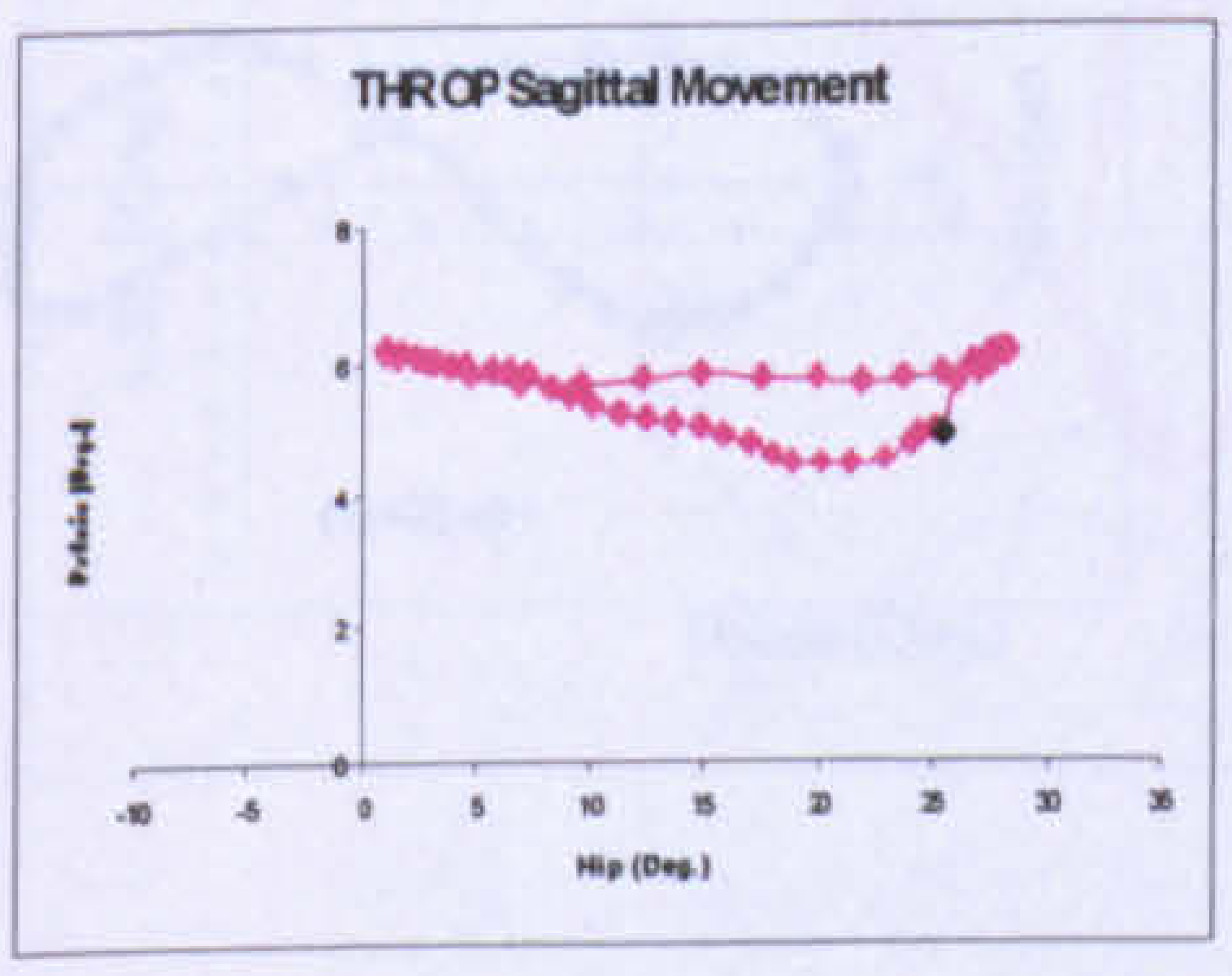
THR OP ▬

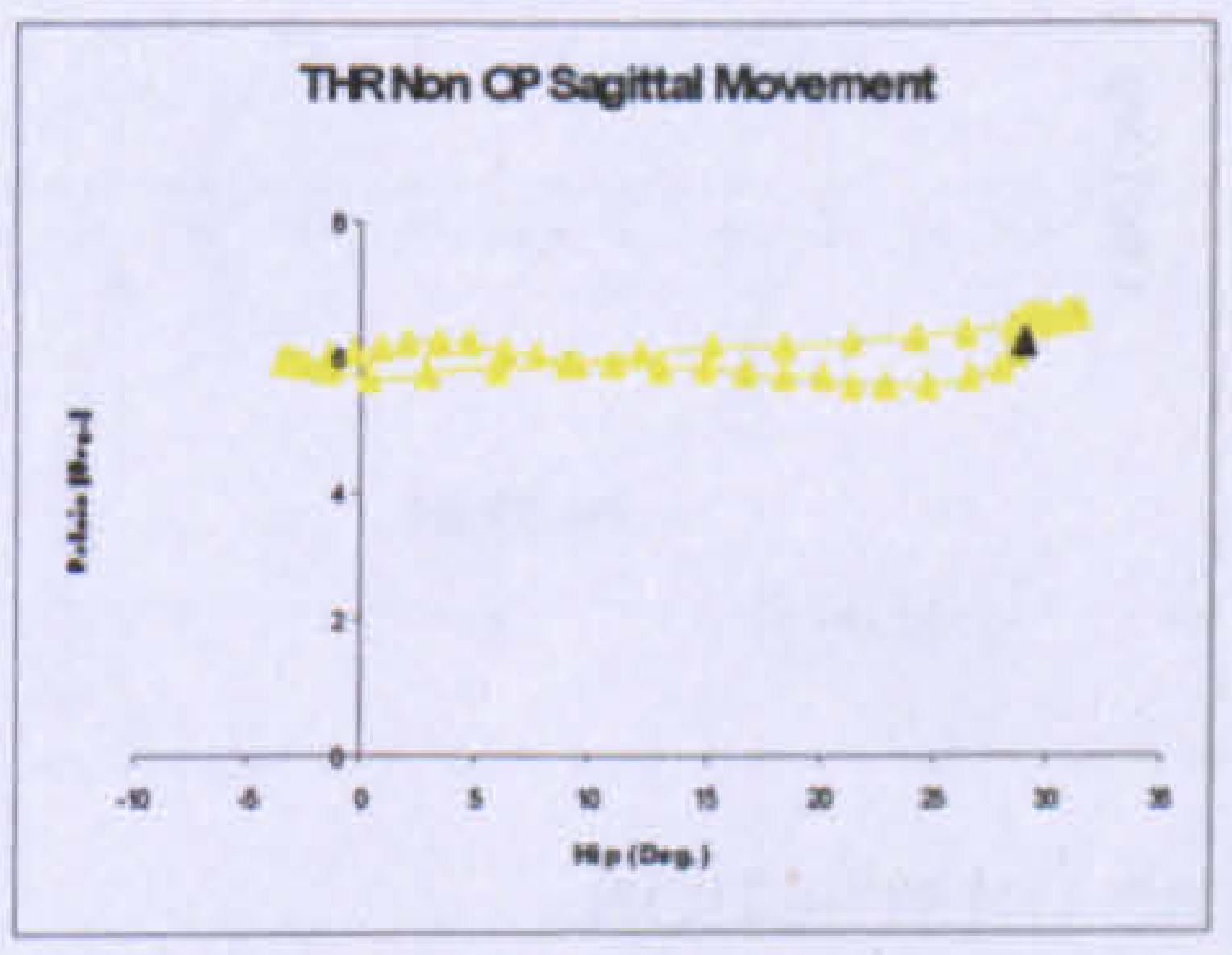
THR Non OP ▬

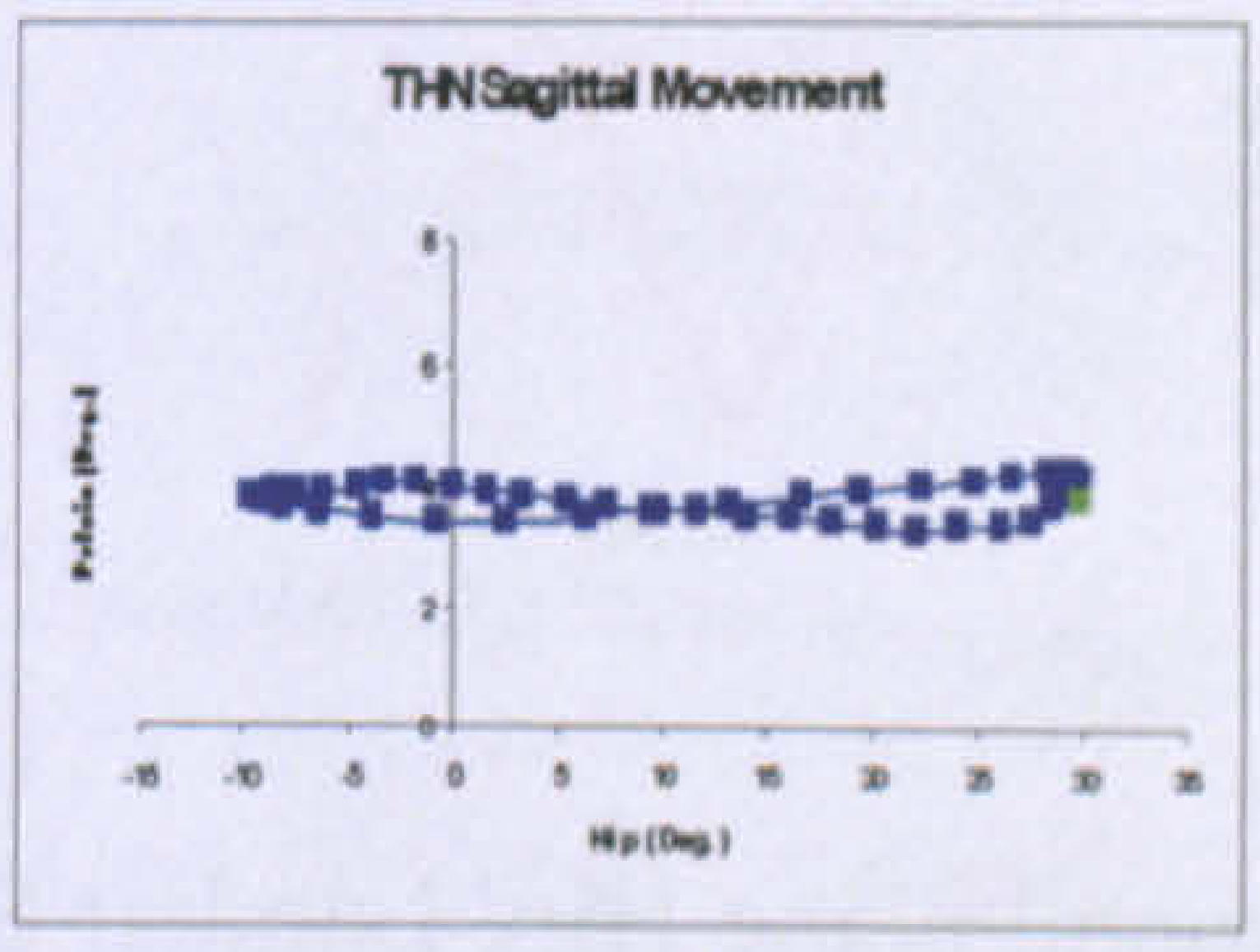
THN ▬

Symbol in contrasting colour represents the joint position at heel strike - the start of the gait cycle

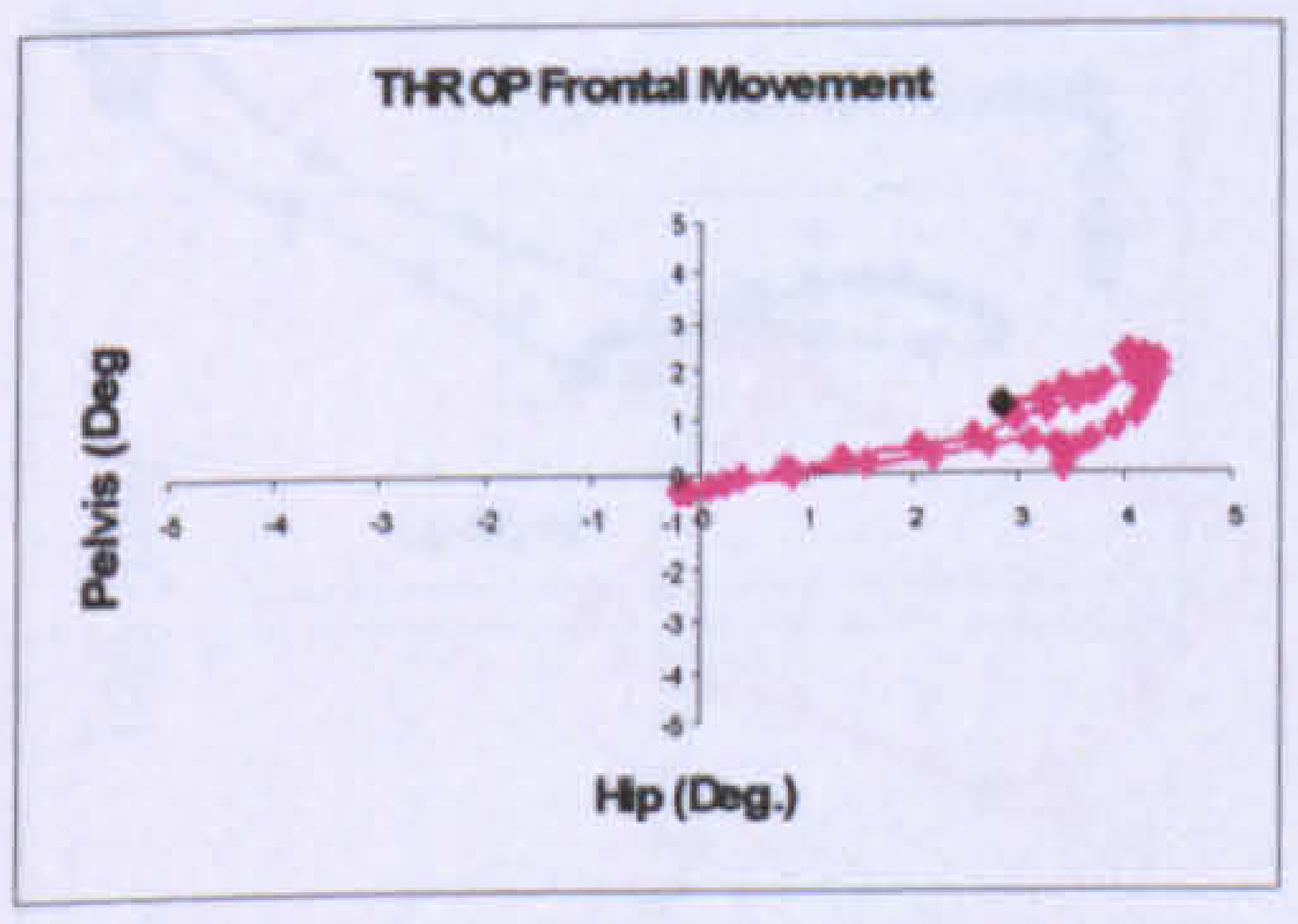
Sagittal plane Hip/ Pelvic interaction

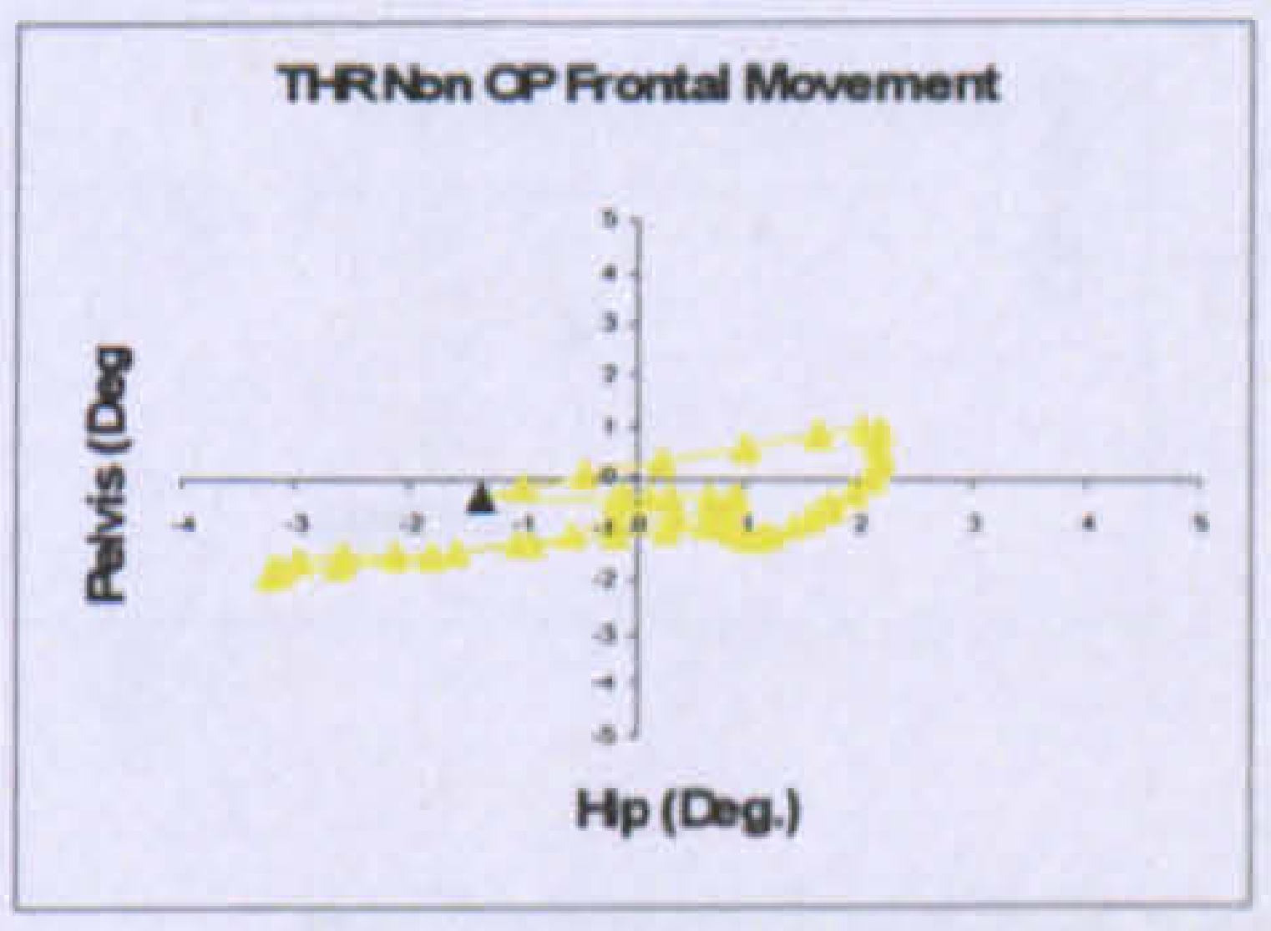


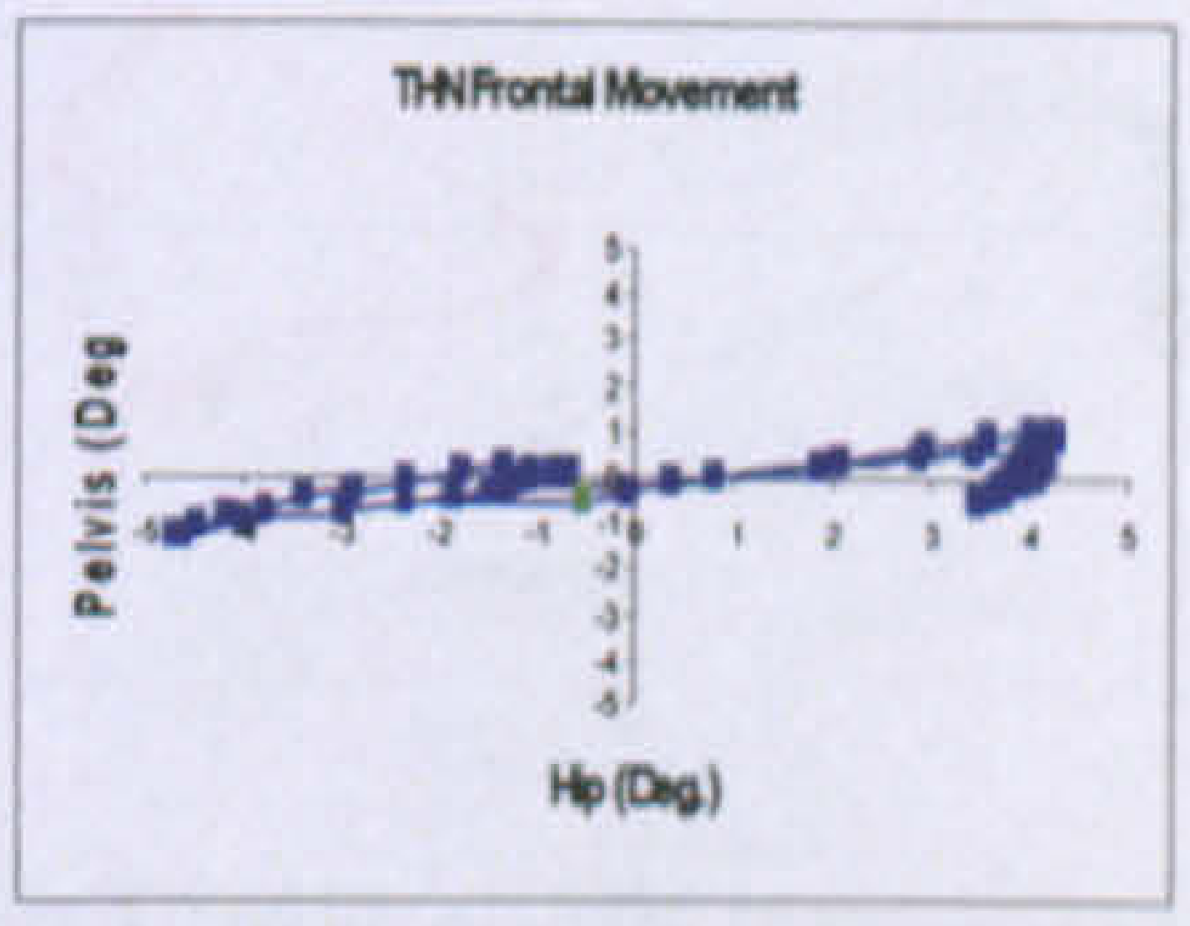




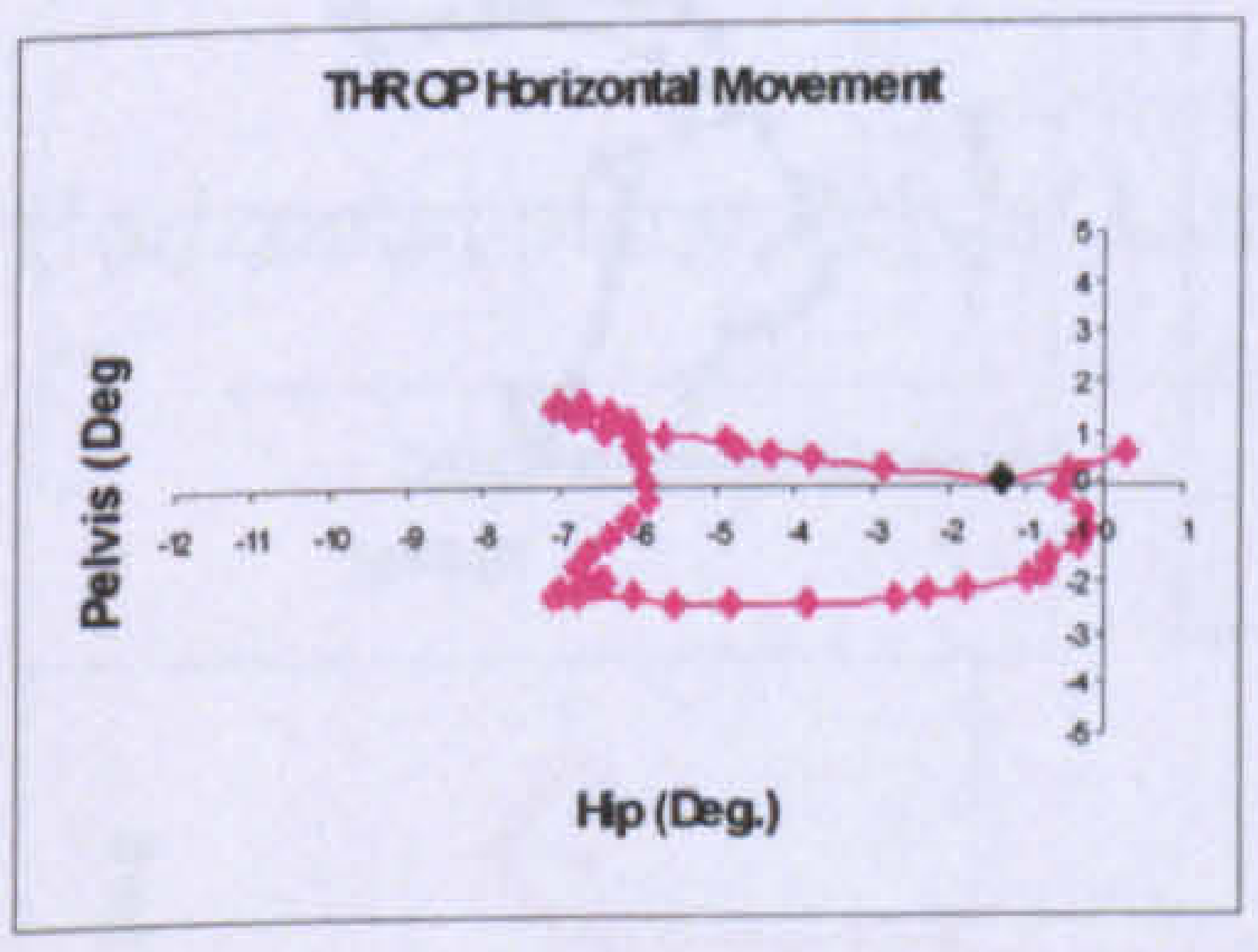
Frontal plane Hip/ Pelvic interaction

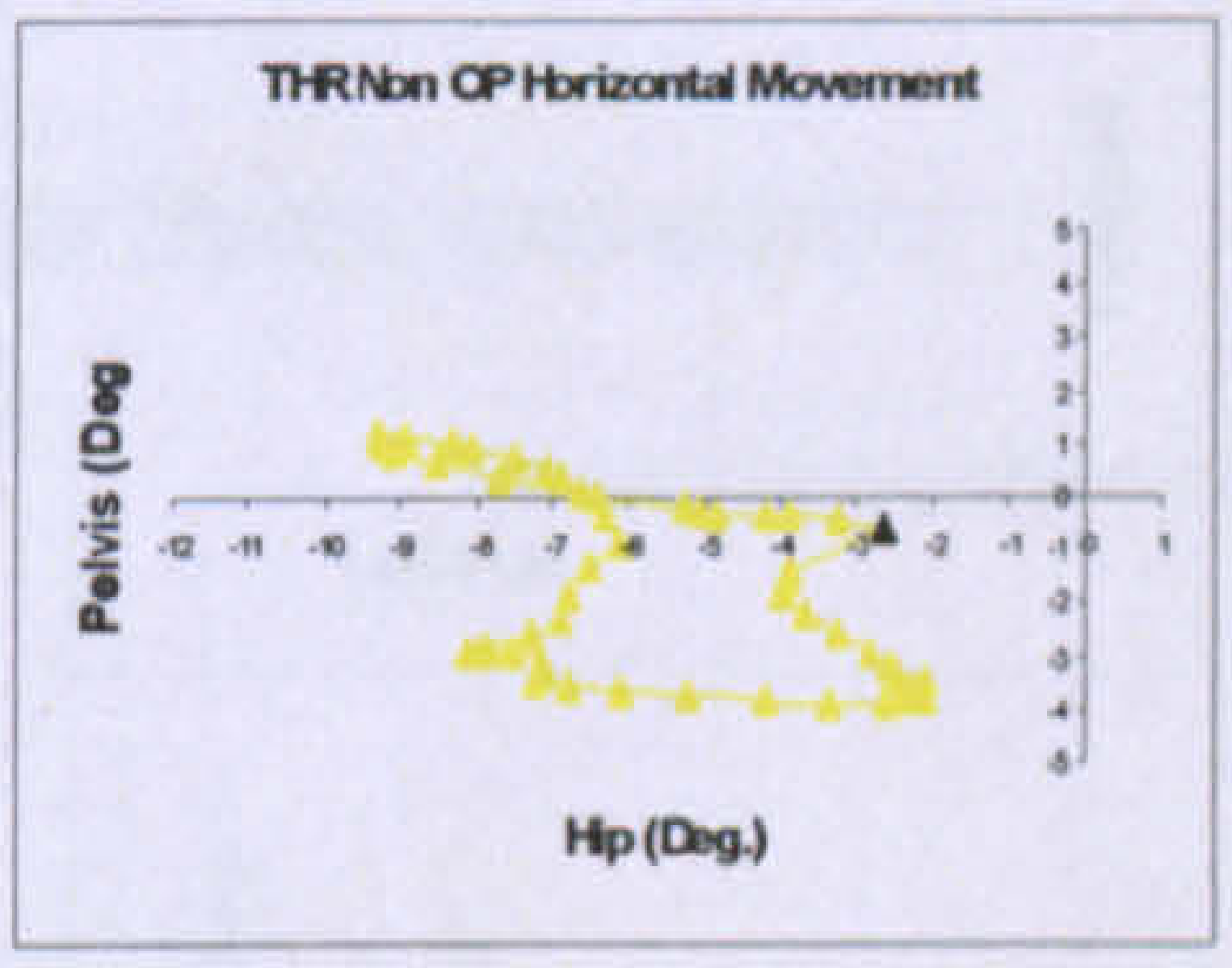


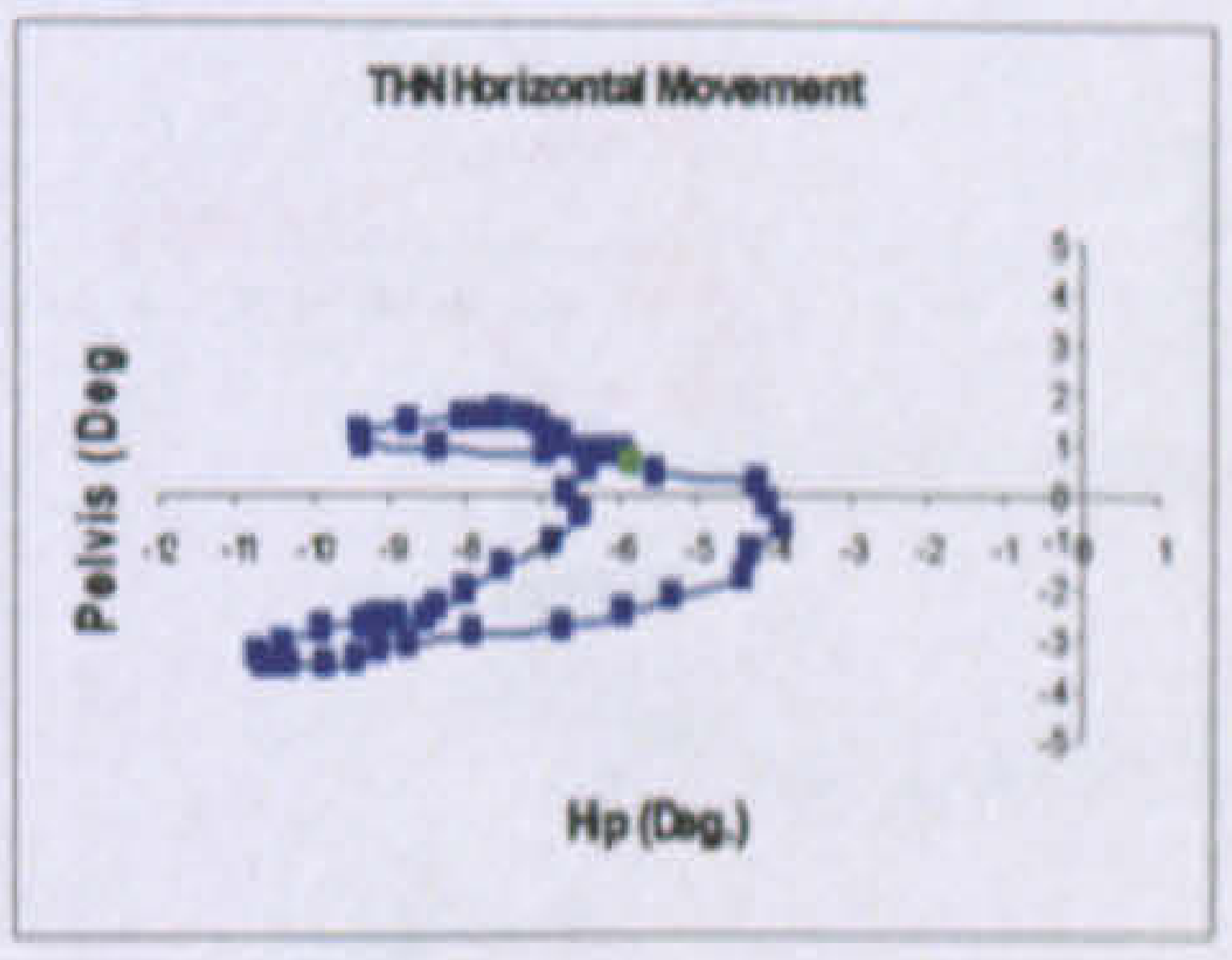




Horizontal plane Hip/ Pelvic interaction







Key for all figures:

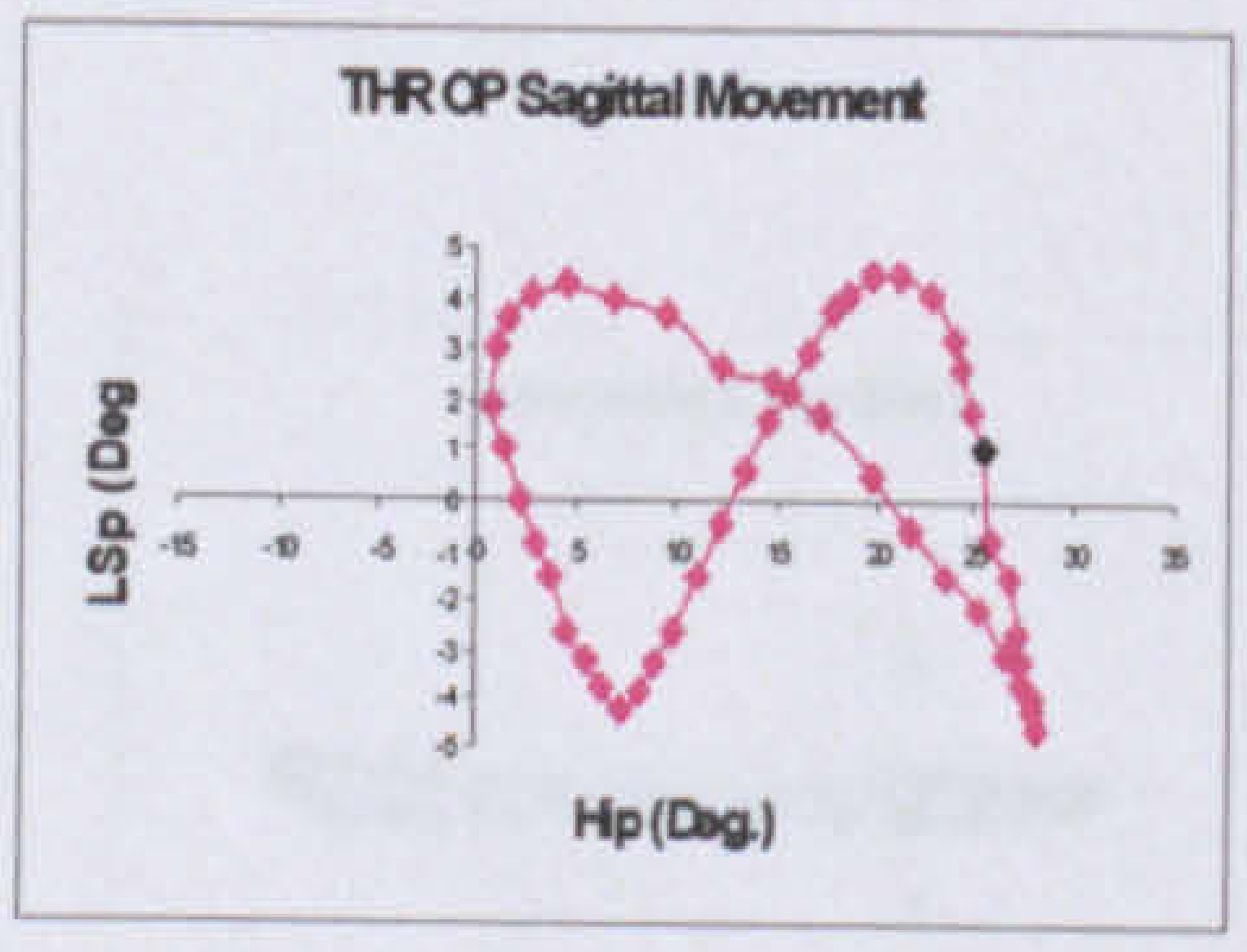
THR OP

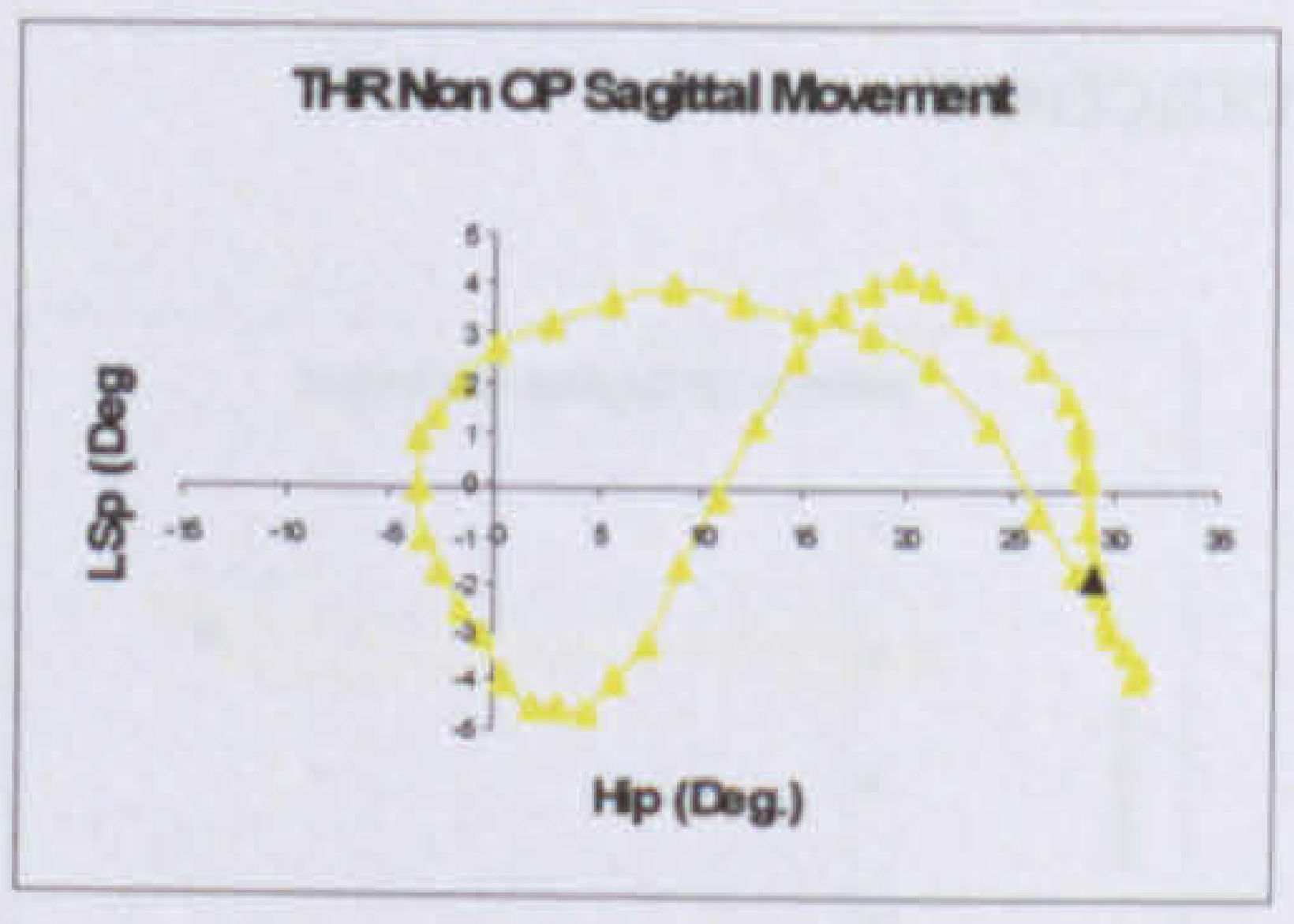
THR Non OP

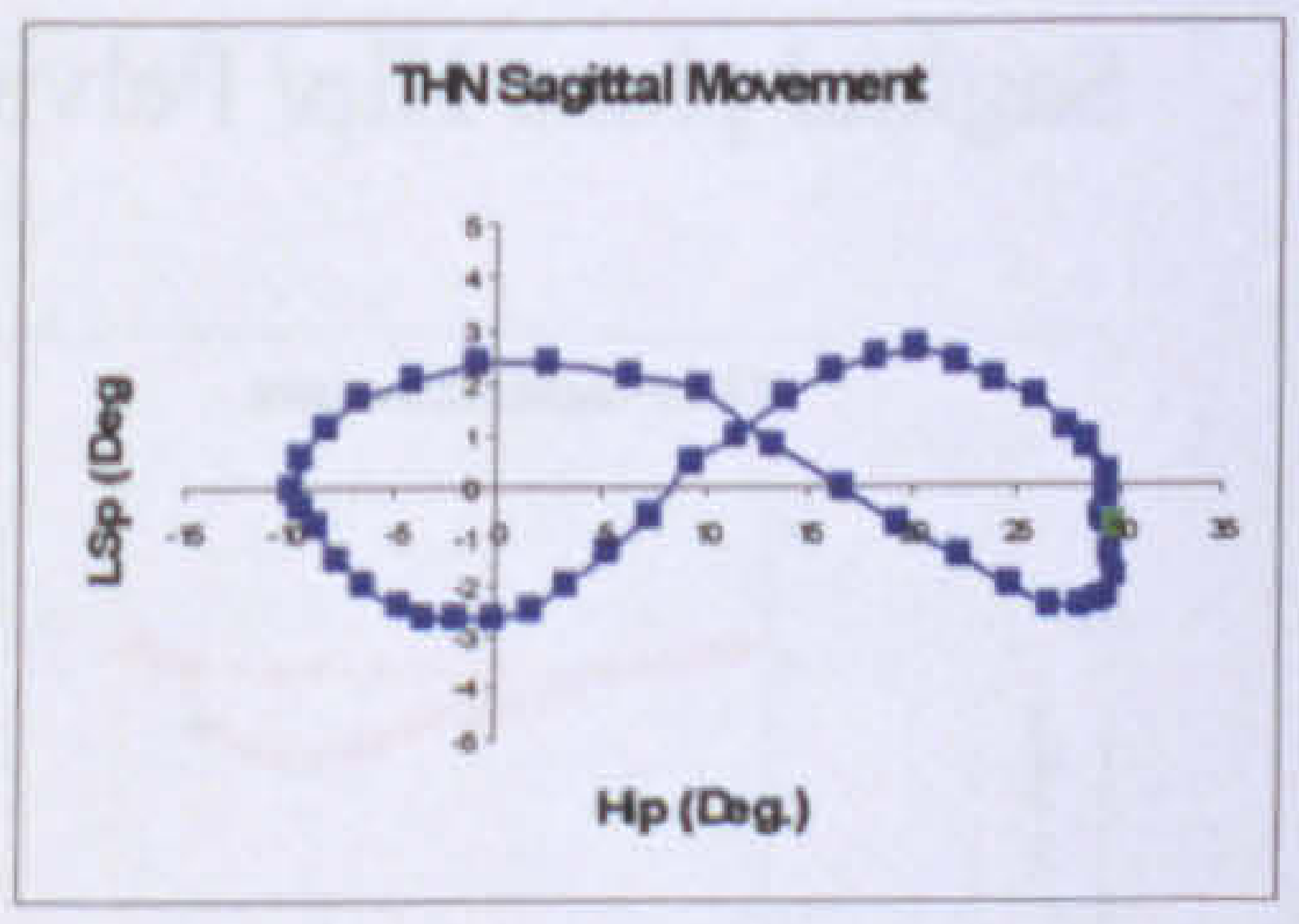
THN

Symbol in contrasting colour represents the joint position at heel strike - the start of the gait cycle

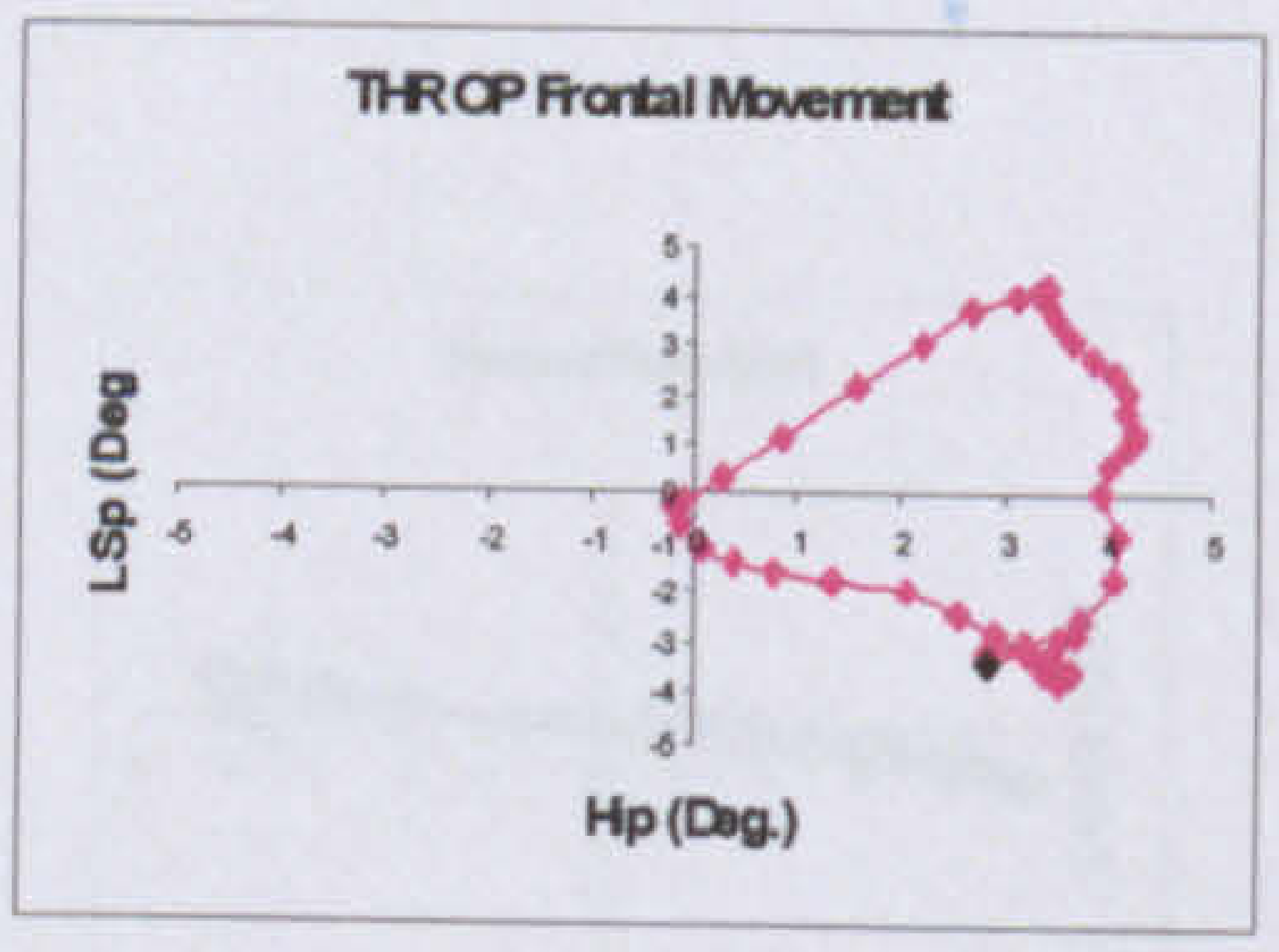
Sagittal plane Hip/ Lumbar Spine interaction

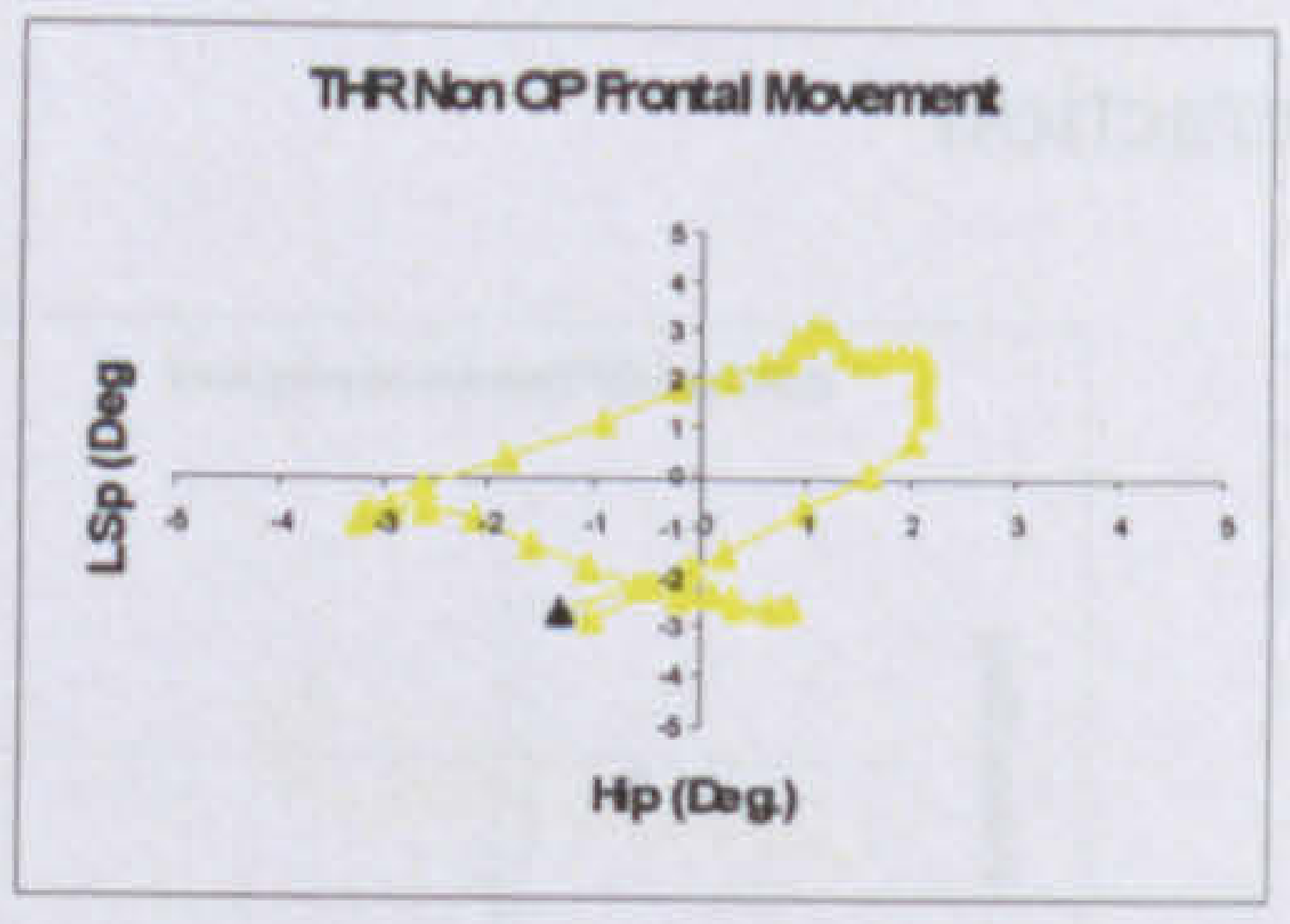


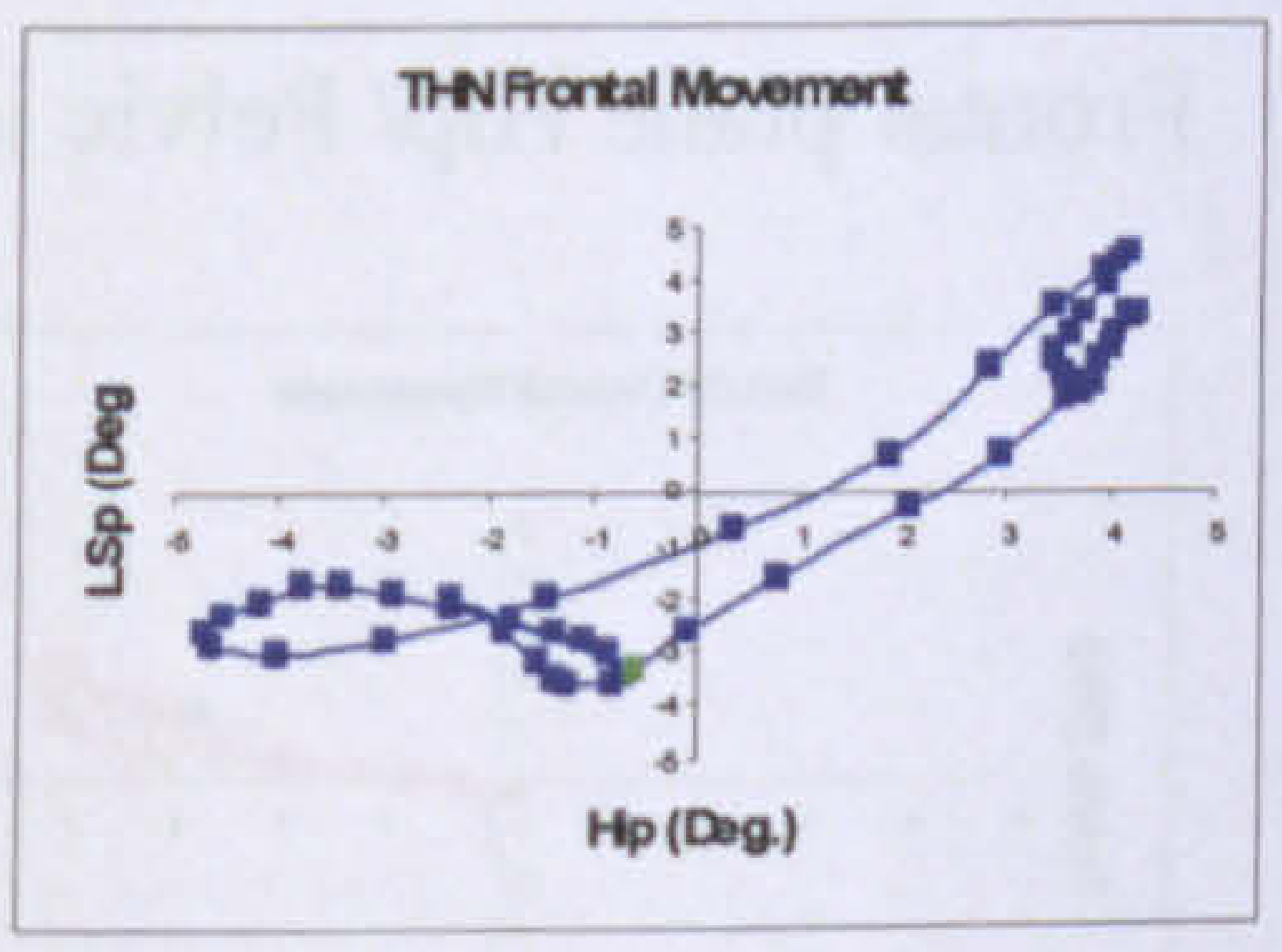




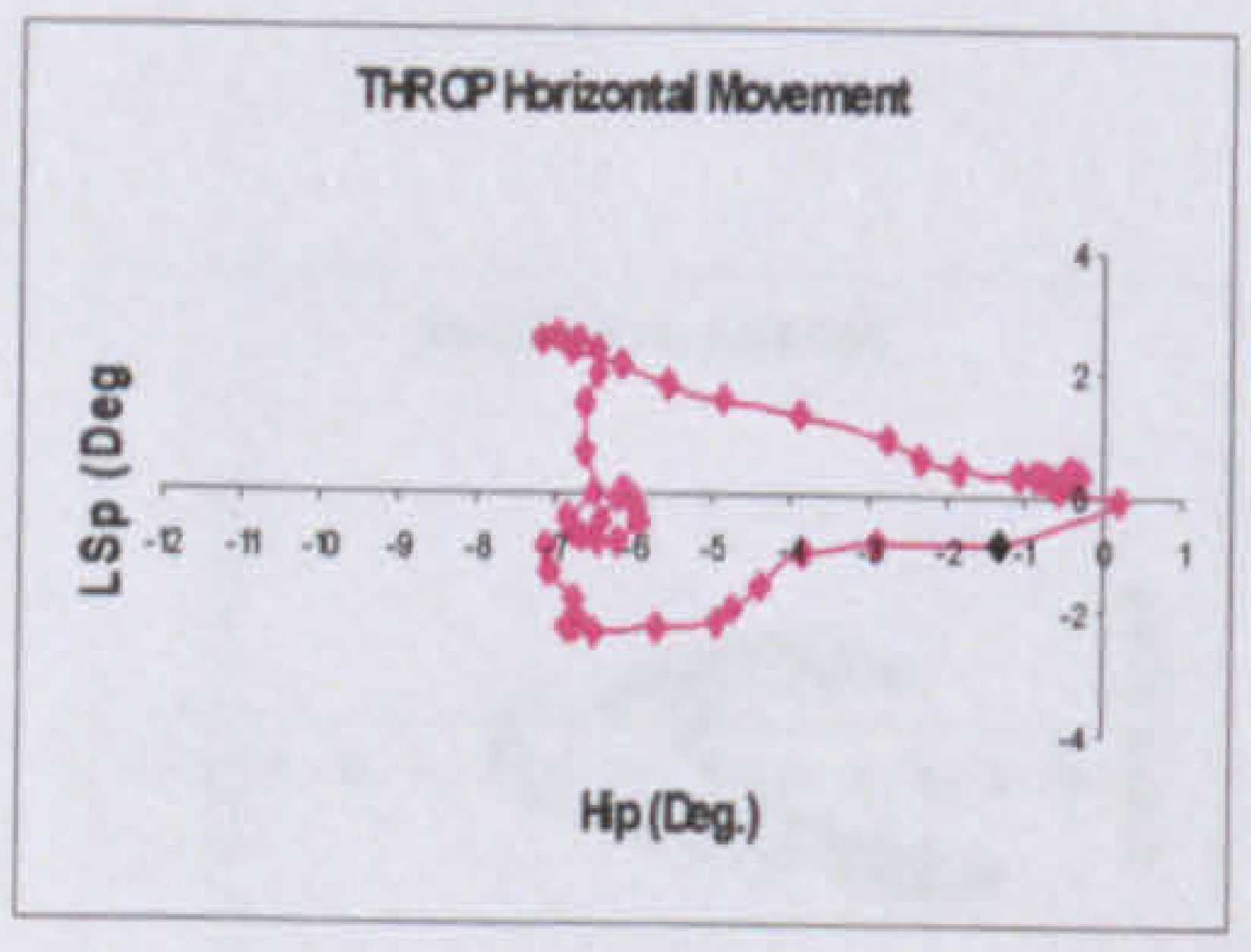
Frontal plane Hip/ Lumbar Spine interaction

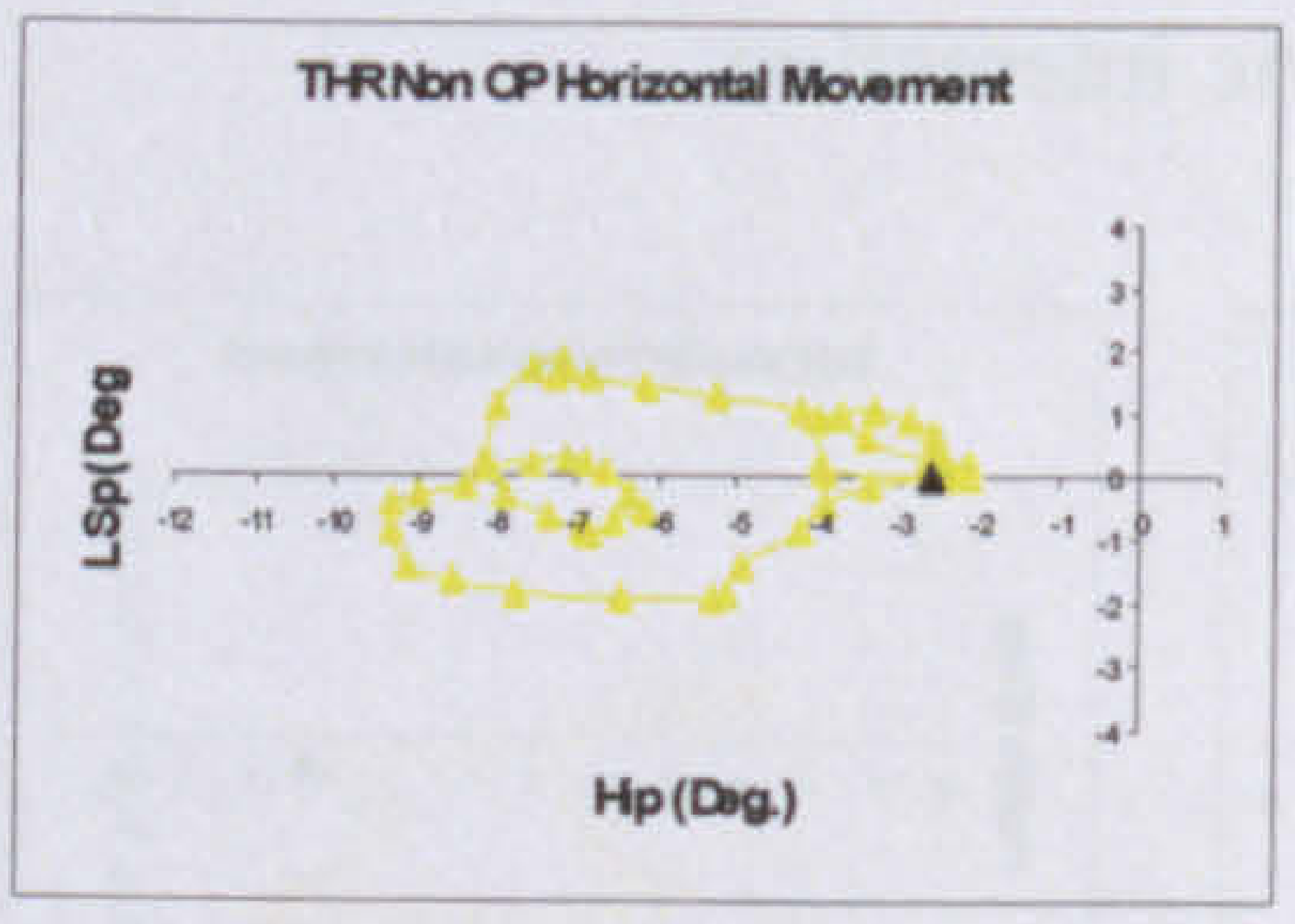


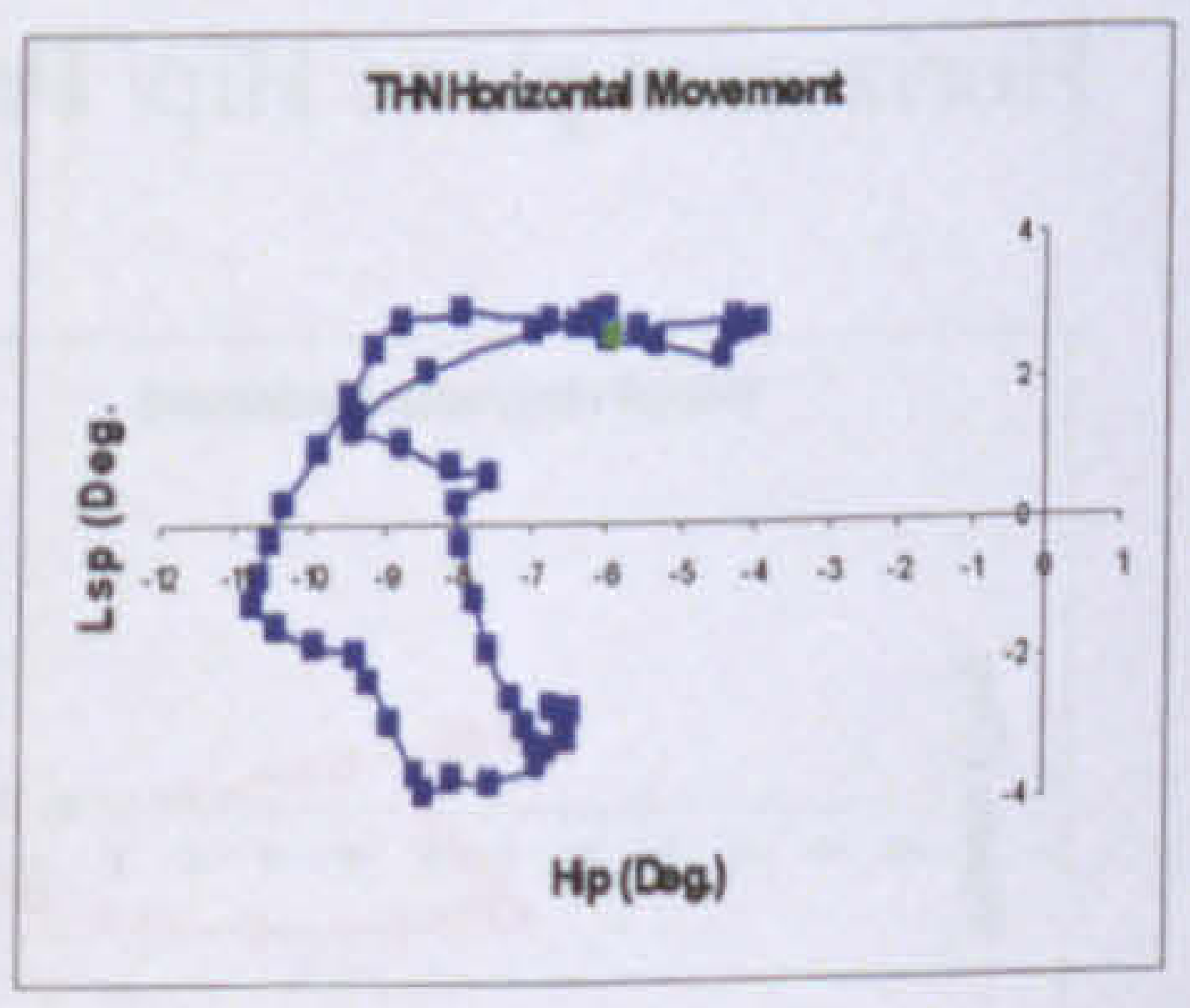




Horizontal plane Hip/ Lumbar Spine interaction







Key for all figures:

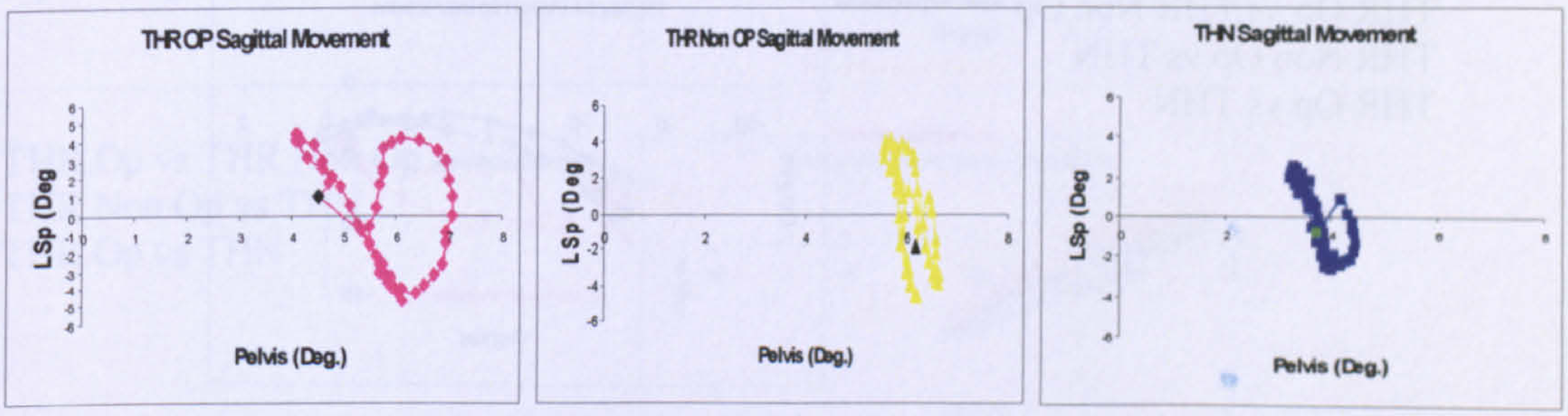
THR OP ▬

THR Non OP ▬

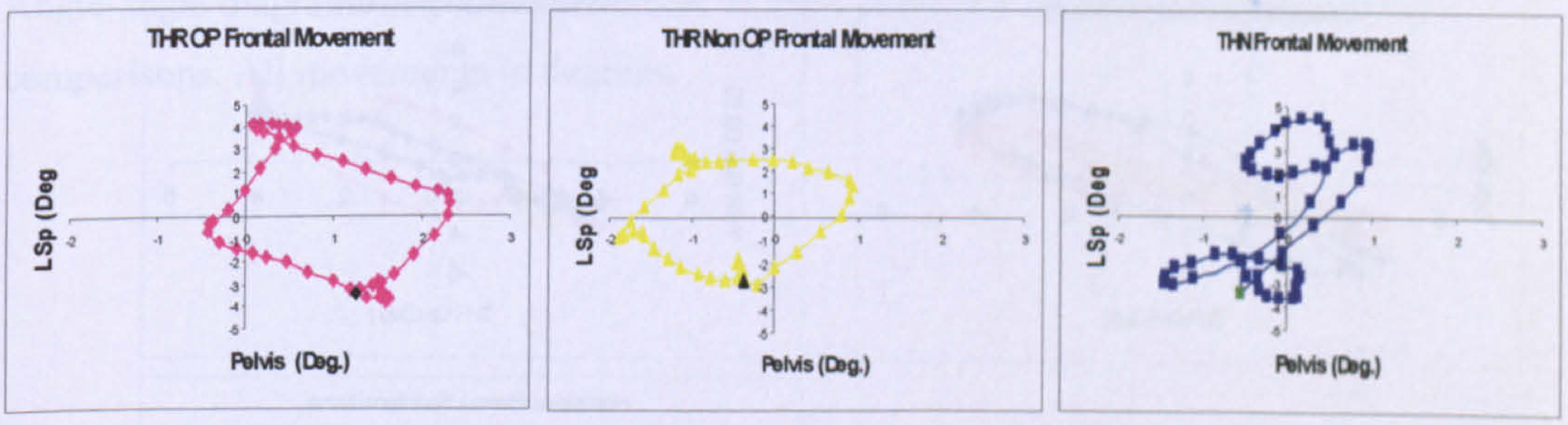
THN ▬

Symbol in contrasting colour represents the joint position at heel strike - the start of the gait cycle

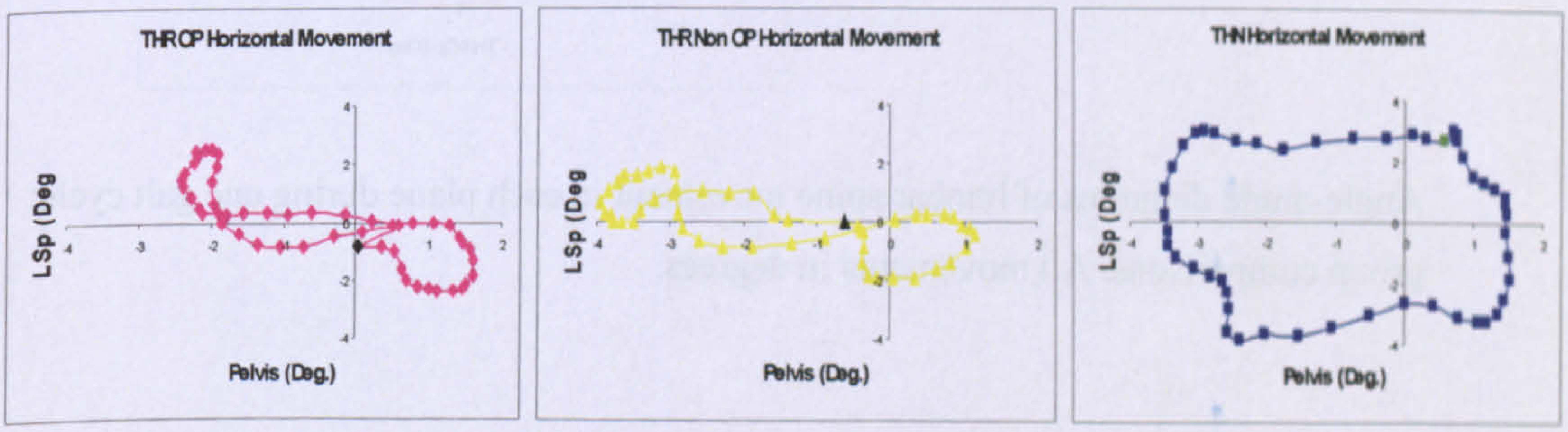
Sagittal plane Pelvis/ Lumbar Spine interaction

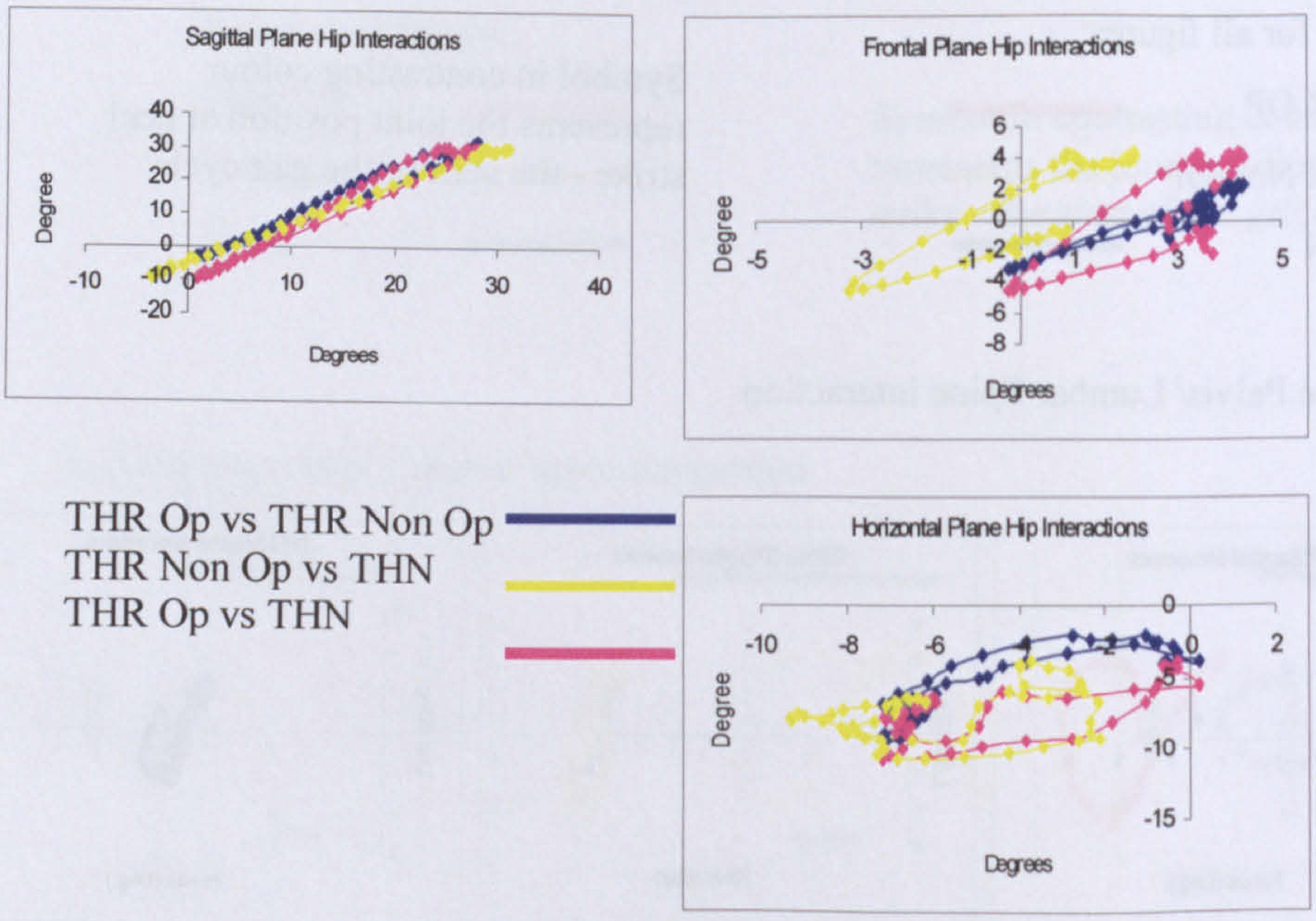


Frontal plane Pelvis/ Lumbar Spine interaction

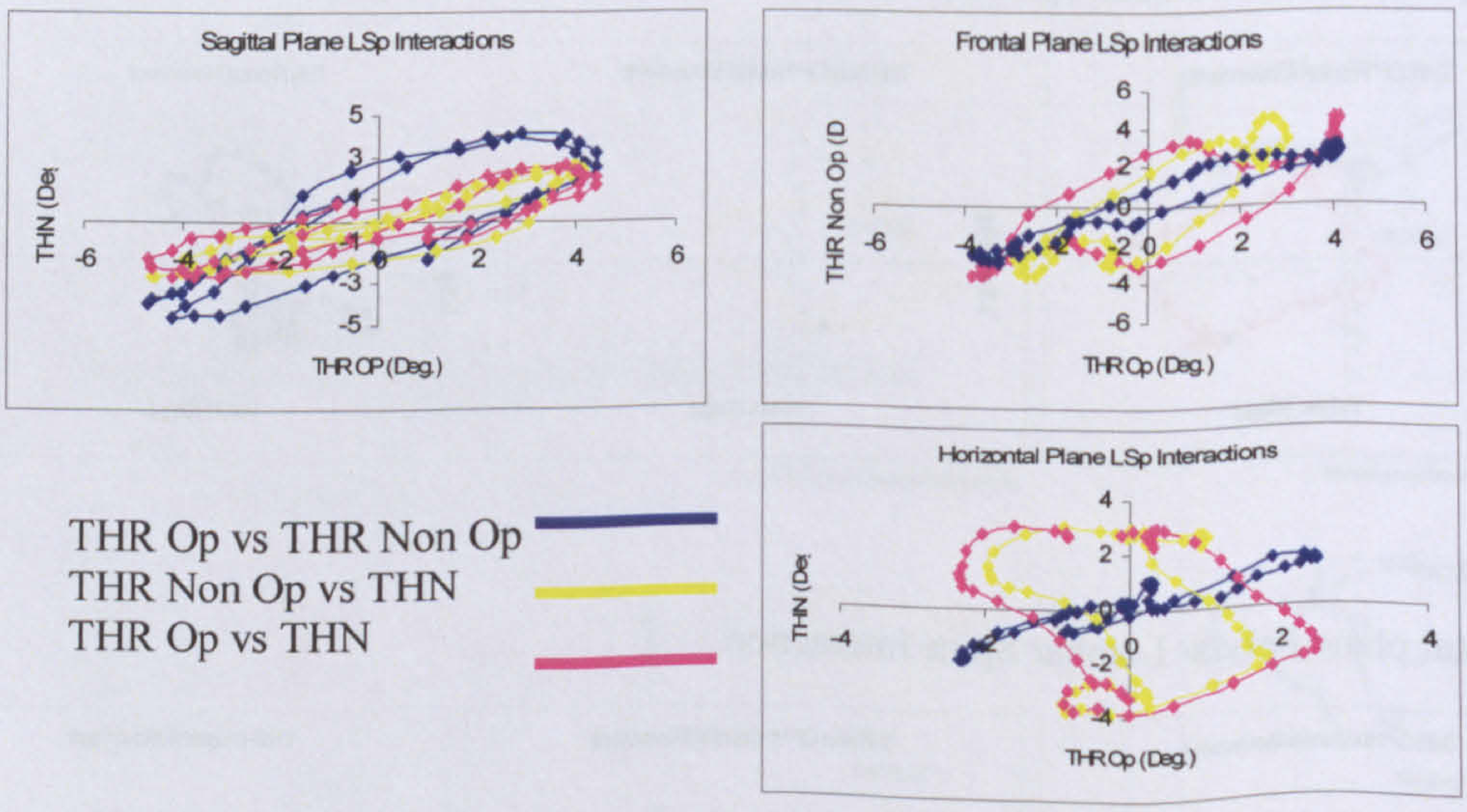


Horizontal plane Pelvis/ Lumbar Spine interaction

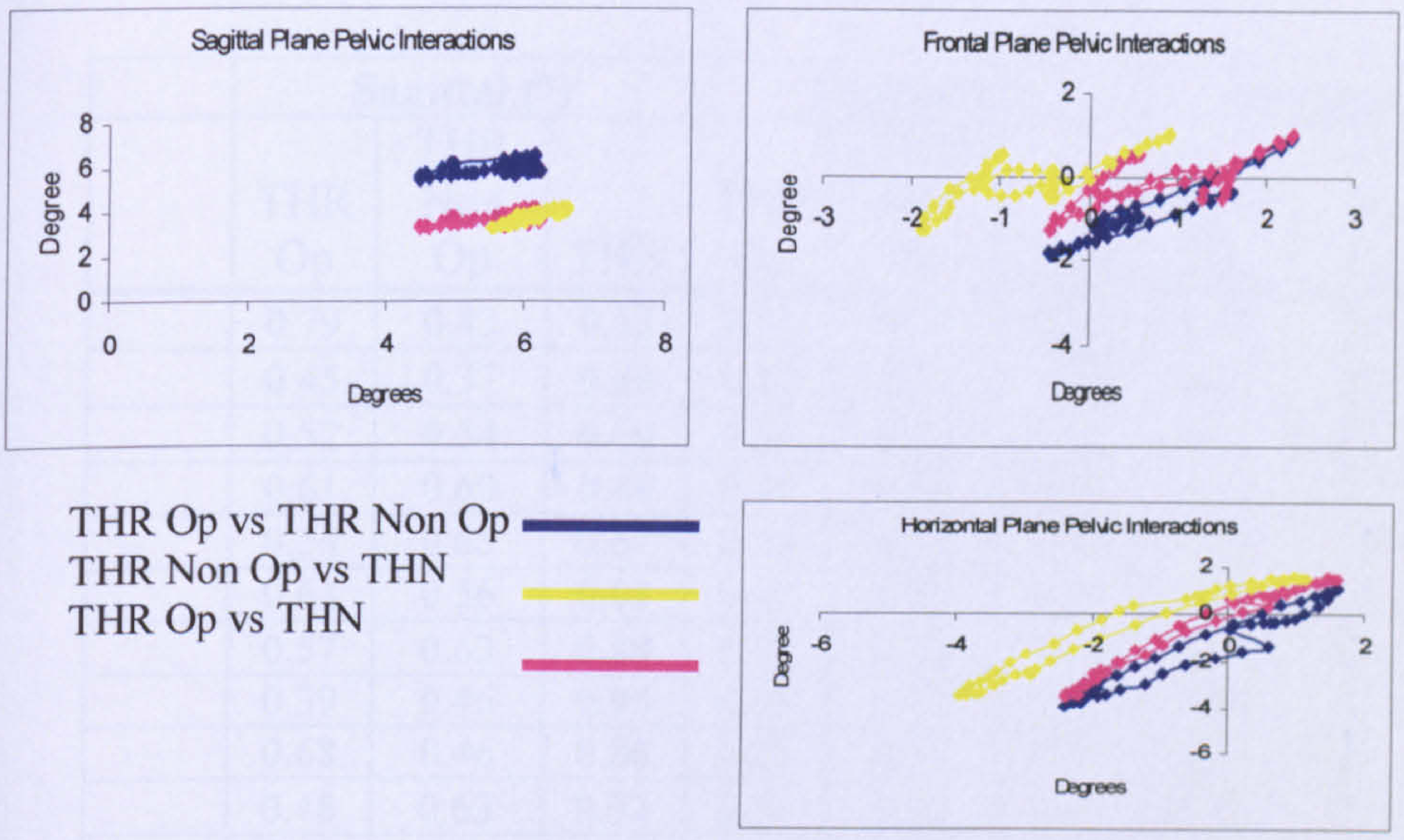




Angle-angle diagrams of hip movement in each plane during one gait cycle: group comparisons. All movements in degrees.



Angle-angle diagrams of lumbar spine movement in each plane during one gait cycle: group comparisons. All movements in degrees.



Angle-angle diagrams of pelvic movement in each plane during one gait cycle: group comparisons. All movements in degrees.

Appendix V: Biomechanical Hip moments

1) Raw Data (n = 24 per group (THR and THN)

a) Range of Hip Moments from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN
	0.79	0.43	0.52	0.34	0.38	0.31	0.11	0.09	0.11
	0.45	0.37	0.60	0.27	0.30	0.18	0.09	0.08	0.08
	0.52	0.54	0.60	0.36	0.24	0.23	0.11	0.09	0.05
	0.61	0.60	0.49	0.19	0.39	0.32	0.09	0.12	0.07
	0.54	0.65	0.67	0.39	0.35	0.33	0.12	0.09	0.17
	0.63	0.56	0.61	0.40	0.35	0.27	0.14	0.11	0.17
	0.57	0.63	0.89	0.39	0.36	0.27	0.14	0.12	0.15
	0.39	0.46	0.95	0.36	0.34	0.36	0.09	0.10	0.17
	0.68	0.46	0.86	0.25	0.34	0.37	0.14	0.10	0.18
	0.48	0.63	0.57	0.34	0.32	0.33	0.10	0.14	0.07
	0.47	0.39	0.70	0.30	0.39	0.35	0.11	0.04	0.13
	0.43	0.63	0.46	0.29	0.26	0.28	0.11	0.12	0.09
	0.53	0.73	0.52	0.29	0.36	0.35	0.11	0.08	0.07
	0.71	0.68	0.84	0.41	0.35	0.28	0.15	0.09	0.11
	0.54	0.60	0.56	0.30	0.34	0.33	0.11	0.11	0.12
	0.45	0.45	0.63	0.30	0.40	0.31	0.11	0.13	0.16
	0.40	0.71	0.80	0.28	0.28	0.32	0.10	0.13	0.12
	0.54	0.72	0.55	0.40	0.35	0.32	0.09	0.06	0.07
	0.49	0.66	0.79	0.36	0.24	0.32	0.11	0.12	0.12
	0.49	0.43	0.57	0.39	0.34	0.37	0.11	0.10	0.09
	0.49	0.47	0.95	0.43	0.42	0.32	0.08	0.13	0.08
	0.59	0.54	0.70	0.47	0.40	0.37	0.14	0.14	0.05
	0.37	0.56	0.54	0.35	0.33	0.40	0.06	0.10	0.11
	0.43	0.53	0.52	0.41	0.40	0.30	0.07	0.07	0.05
Mean	0.53	0.56	0.66	0.35	0.34	0.32	0.11	0.10	0.11
SD	0.10	0.11	0.15	0.07	0.05	0.05	0.02	0.03	0.04

b) Peak Hip Moments from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN
	-0.596	-0.374	-0.497	0.256	0.349	0.271	0.016	0.006	0.012
	-0.401	-0.346	-0.484	0.240	0.268	0.153	0.010	0.007	0.019
	-0.437	-0.435	-0.484	0.332	0.223	0.197	0.013	0.007	0.027
	-0.563	-0.464	-0.436	0.177	0.298	0.273	0.007	0.018	0.008
	-0.448	-0.569	-0.478	0.356	0.309	0.206	0.018	0.010	0.058
	-0.528	-0.463	-0.538	0.355	0.306	0.247	0.017	0.010	0.011
	-0.471	-0.512	-0.662	0.353	0.326	0.216	0.022	0.025	0.043
	-0.296	-0.400	-0.720	0.320	0.320	0.299	0.017	0.008	0.039
	-0.563	-0.402	-0.681	0.218	0.318	0.327	0.019	0.008	0.035
	-0.424	-0.530	-0.477	0.290	0.292	0.267	0.014	0.012	0.014
	-0.431	-0.311	-0.557	0.252	0.360	0.309	0.012	0.013	0.029
	-0.365	-0.513	-0.409	0.270	0.182	0.227	0.007	0.036	0.011
	-0.384	-0.616	-0.448	0.252	0.301	0.314	0.022	0.024	0.010
	-0.486	-0.602	-0.705	0.346	0.290	0.208	0.033	0.023	0.020
	-0.470	-0.482	-0.534	0.279	0.283	0.292	0.008	0.018	0.013
	-0.396	-0.380	-0.449	0.286	0.355	0.193	0.004	0.013	0.054
	-0.349	-0.609	-0.725	0.264	0.175	0.230	0.005	0.017	0.012
	-0.463	-0.583	-0.377	0.344	0.289	0.265	0.012	0.023	0.012
	-0.449	-0.539	-0.720	0.275	0.178	0.229	0.010	0.025	0.012
	-0.456	-0.368	-0.507	0.306	0.315	0.317	0.012	0.012	0.009
	-0.404	-0.417	-0.720	0.354	0.377	0.281	0.013	0.011	0.035
	-0.475	-0.409	-0.557	0.422	0.336	0.315	0.018	0.025	0.022
	-0.280	-0.430	-0.454	0.294	0.261	0.343	0.010	0.012	0.010
	-0.354	-0.438	-0.448	0.338	0.367	0.279	0.009	0.011	0.028
Mean	-0.44	-0.47	-0.54	0.30	0.29	0.26	0.01	0.02	0.02
SD	0.08	0.09	0.11	0.05	0.06	0.05	0.01	0.01	0.01

c) Hip moments at Heel Strike from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN
	0.154	0.024	-0.002	-0.034	0.019	0.017	0.013	0.001	-0.003
	0.018	0.011	0.034	-0.007	-0.001	0.040	0.002	0.001	-0.002
	0.046	0.057	0.034	0.015	0.020	0.028	-0.002	-0.001	0.002
	-0.011	0.138	0.003	0.011	0.021	0.027	-0.002	0.015	-0.004
	0.063	0.039	-0.052	0.010	0.021	-0.027	-0.006	0.003	0.012
	-0.002	-0.072	0.036	0.006	0.019	0.031	-0.004	-0.016	0.001
	0.102	0.118	-0.020	0.031	-0.017	0.005	0.002	0.025	-0.006
	0.083	0.013	0.054	-0.014	0.013	-0.004	0.010	-0.004	0.012
	-0.011	0.021	0.183	0.024	0.023	-0.038	-0.011	-0.008	0.035
	0.055	0.083	0.067	0.009	-0.001	0.016	-0.001	0.012	0.008
	-0.034	0.011	0.025	-0.006	-0.016	0.030	0.000	0.004	-0.004
	0.004	0.024	0.020	0.023	0.043	0.007	-0.009	-0.016	0.004
	0.053	0.005	0.029	-0.020	0.000	0.023	0.006	-0.001	-0.002
	0.079	-0.021	0.063	-0.022	0.018	0.006	0.011	-0.004	0.011
	-0.006	0.056	-0.003	-0.002	-0.014	0.019	-0.005	0.005	-0.003
	0.037	0.055	-0.049	0.028	-0.017	-0.025	-0.007	0.011	0.012
	0.013	0.071	0.014	0.010	0.002	-0.019	-0.003	0.011	0.005
	0.007	0.030	0.014	-0.022	-0.008	-0.023	0.006	0.002	0.006
	0.009	0.045	0.014	-0.013	0.023	-0.019	0.004	-0.006	0.005
	-0.011	0.003	0.003	-0.016	0.008	0.032	0.003	-0.003	-0.005
	-0.020	-0.033	0.054	0.003	-0.004	0.018	0.005	-0.004	-0.004
	0.062	-0.014	0.025	-0.018	0.000	0.032	0.015	-0.009	0.008
	-0.023	0.037	0.051	-0.019	0.020	-0.011	0.003	-0.003	0.010
	-0.035	-0.030	0.029	-0.018	0.005	0.035	0.005	-0.007	0.002
Mean	0.026	0.028	0.026	-0.002	0.007	0.008	0.001	0.000	0.004
SD	0.047	0.047	0.045	0.018	0.016	0.023	0.007	0.010	0.009

d) Hip moments at Toe off from Individuals (n=24 per group)

	Sagittal (°)			Frontal (°)			Horizontal (°)		
	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN	THR Op	THR Non Op	THN
	-0.001	-0.015	0.010	-0.035	-0.020	-0.020	0.013	0.007	0.012
	-0.007	-0.055	0.005	-0.015	-0.030	-0.010	0.006	0.007	0.008
	-0.040	-0.020	0.007	0.003	-0.015	-0.010	-0.008	0.005	0.010
	-0.010	-0.055	-0.030	-0.012	-0.065	-0.040	0.005	0.012	0.007
	-0.120	-0.040	-0.060	0.075	-0.040	-0.010	-0.040	0.008	-0.009
	-0.090	-0.020	0.035	0.025	-0.040	-0.010	-0.020	0.004	0.011
	-0.010	-0.030	-0.110	-0.007	-0.035	-0.050	0.005	0.005	-0.002
	-0.015	0.002	-0.030	-0.040	-0.020	-0.040	0.007	0.005	0.007
	-0.145	-0.005	-0.090	-0.020	-0.010	-0.045	-0.015	0.002	-0.005
	-0.150	-0.060	-0.115	-0.010	-0.030	-0.025	-0.001	0.001	-0.014
	0.004	-0.004	-0.040	-0.020	-0.015	0.015	0.007	0.005	-0.002
	-0.075	-0.045	-0.100	-0.025	-0.015	-0.030	0.002	0.004	-0.006
	-0.075	-0.070	-0.005	-0.010	-0.050	-0.010	-0.013	0.005	0.003
	-0.020	-0.025	-0.065	-0.030	-0.030	-0.040	0.005	0.007	0.001
	-0.030	0.007	0.010	-0.025	0.005	-0.025	0.008	0.004	0.013
	-0.010	-0.015	-0.090	-0.005	-0.045	-0.020	0.004	-0.004	0.001
	-0.035	-0.005	-0.035	-0.010	-0.060	-0.035	0.001	0.005	-0.039
	-0.040	-0.010	-0.030	-0.035	-0.050	0.006	0.001	0.003	-0.004
	-0.070	-0.035	-0.065	-0.050	0.015	-0.065	0.008	-0.033	0.006
	0.003	-0.010	-0.035	-0.025	-0.040	-0.045	0.010	0.006	0.008
	-0.070	0.004	-0.100	-0.006	-0.040	-0.035	0.009	0.009	0.004
	-0.015	-0.090	-0.095	-0.025	-0.065	-0.045	0.004	-0.009	0.004
	-0.035	-0.020	-0.030	-0.040	-0.030	-0.035	0.004	0.009	-0.040
	-0.045	-0.010	-0.010	-0.020	0.170	-0.020	-0.001	-0.009	0.006
Mean	-0.05	-0.03	-0.04	-0.02	-0.02	-0.03	0.000	0.002	-0.001
SD	0.04	0.03	0.04	0.02	0.05	0.02	0.012	0.009	0.013

e) Mean Sagittal plane hip moments through the Gait Cycle (°) (n=24)

% Time	THR OP	THR NON OP	THN
0	0.24	0.25	0.24
2	0.27	0.29	0.32
4	0.19	0.19	0.16
6	0.12	0.17	0.08
8	0.06	0.10	-0.01
10	0.01	0.04	-0.07
12	-0.04	-0.02	-0.13
14	-0.09	-0.08	-0.18
16	-0.13	-0.13	-0.21
18	-0.15	-0.16	-0.23
20	-0.17	-0.18	-0.23
22	-0.19	-0.18	-0.23
24	-0.20	-0.19	-0.24
26	-0.21	-0.20	-0.24
28	-0.22	-0.22	-0.26
30	-0.23	-0.23	-0.28
32	-0.24	-0.24	-0.30
34	-0.26	-0.26	-0.32
36	-0.28	-0.29	-0.34
38	-0.31	-0.32	-0.38
40	-0.34	-0.36	-0.42
42	-0.37	-0.40	-0.48
44	-0.41	-0.45	-0.54
46	-0.44	-0.49	-0.60
48	-0.47	-0.51	-0.63
50	-0.48	-0.52	-0.61
52	-0.43	-0.48	-0.57
54	-0.37	-0.41	-0.52
56	-0.30	-0.34	-0.45
58	-0.24	-0.29	-0.35
60	-0.19	-0.19	-0.27
62	-0.10	-0.11	-0.16
64	-0.06	-0.05	-0.09
66	-0.03	-0.03	-0.06
68	-0.03	-0.02	-0.04
70	-0.03	-0.02	-0.02
72	-0.02	-0.02	-0.01
74	-0.01	-0.02	0.00
76	0.00	-0.01	0.01
78	0.01	0.00	0.02
80	0.02	0.01	0.04
82	0.04	0.03	0.05
84	0.04	0.06	0.07
86	0.05	0.08	0.08
88	0.07	0.10	0.10
90	0.08	0.10	0.10
92	0.08	0.09	0.09
94	0.08	0.08	0.06
96	0.08	0.07	0.05
98	0.06	0.05	0.02
100	0.04	0.04	0.00

f) Mean Frontal plane hip moments through the Gait Cycle (°) (n=24)

% Time	THR OP	THR NON OP	THN
0	-0.003	0.012	0.014
2	0.031	0.010	0.011
4	0.049	0.021	0.053
6	0.094	0.079	0.138
8	0.173	0.165	0.219
10	0.249	0.234	0.283
12	0.314	0.302	0.321
14	0.368	0.353	0.364
16	0.408	0.385	0.391
18	0.432	0.412	0.392
20	0.442	0.428	0.388
22	0.444	0.431	0.379
24	0.445	0.428	0.371
26	0.444	0.426	0.364
28	0.445	0.426	0.362
30	0.442	0.421	0.356
32	0.434	0.417	0.356
34	0.428	0.418	0.363
36	0.426	0.416	0.364
38	0.427	0.410	0.363
40	0.428	0.410	0.364
42	0.422	0.409	0.364
44	0.408	0.389	0.363
46	0.390	0.364	0.346
48	0.358	0.341	0.311
50	0.313	0.305	0.263
52	0.251	0.249	0.197
54	0.165	0.173	0.108
56	0.078	0.089	0.032
58	0.015	0.022	-0.024
60	-0.022	-0.021	-0.055
62	-0.034	-0.041	-0.062
64	-0.030	-0.040	-0.047
66	-0.021	-0.032	-0.031
68	-0.013	-0.019	-0.026
70	-0.008	-0.008	-0.022
72	-0.004	-0.001	-0.016
74	-0.003	0.007	-0.011
76	-0.003	0.013	-0.006
78	-0.002	0.017	0.000
80	0.002	0.019	0.001
82	0.004	0.018	0.003
84	0.003	0.017	0.007
86	-0.001	0.011	0.009
88	-0.005	0.008	0.014
90	-0.011	0.002	0.017
92	-0.014	-0.001	0.014
94	-0.014	-0.003	0.008
96	-0.012	-0.006	0.010
98	-0.012	-0.007	0.012
100	-0.010	-0.003	0.008

g) Mean Horizontal plane hip moments through the Gait Cycle (°) (n=24)

% Time	THR OP	THR NON OP	THN
0	0.002	0.001	0.007
2	0.000	0.013	0.019
4	-0.015	-0.003	-0.014
6	-0.040	-0.023	-0.045
8	-0.069	-0.053	-0.079
10	-0.090	-0.078	-0.104
12	-0.109	-0.098	-0.123
14	-0.125	-0.111	-0.132
16	-0.134	-0.121	-0.129
18	-0.136	-0.127	-0.118
20	-0.135	-0.125	-0.106
22	-0.130	-0.117	-0.095
24	-0.124	-0.106	-0.084
26	-0.118	-0.096	-0.074
28	-0.112	-0.087	-0.063
30	-0.105	-0.077	-0.052
32	-0.099	-0.070	-0.043
34	-0.096	-0.066	-0.038
36	-0.094	-0.063	-0.037
38	-0.094	-0.061	-0.038
40	-0.096	-0.062	-0.041
42	-0.097	-0.066	-0.047
44	-0.099	-0.070	-0.051
46	-0.104	-0.074	-0.062
48	-0.105	-0.080	-0.072
50	-0.102	-0.084	-0.079
52	-0.093	-0.084	-0.078
54	-0.076	-0.076	-0.068
56	-0.052	-0.056	-0.047
58	-0.032	-0.033	-0.022
60	-0.016	-0.013	-0.009
62	-0.003	0.001	0.003
64	0.002	0.008	0.004
66	0.002	0.008	-0.001
68	0.001	0.006	0.002
70	-0.001	0.002	0.002
72	-0.002	0.000	0.000
74	-0.001	-0.003	0.002
76	0.001	-0.004	0.001
78	0.002	-0.005	0.002
80	0.003	-0.004	0.002
82	0.004	-0.001	0.003
84	0.005	0.001	0.004
86	0.007	0.006	0.007
88	0.009	0.009	0.012
90	0.011	0.010	0.013
92	0.011	0.009	0.012
94	0.011	0.009	0.009
96	0.010	0.007	0.007
98	0.008	0.005	0.007
100	0.006	0.003	0.009

h) Mean THN hip planar moments through the Gait Cycle (°) (n=24)

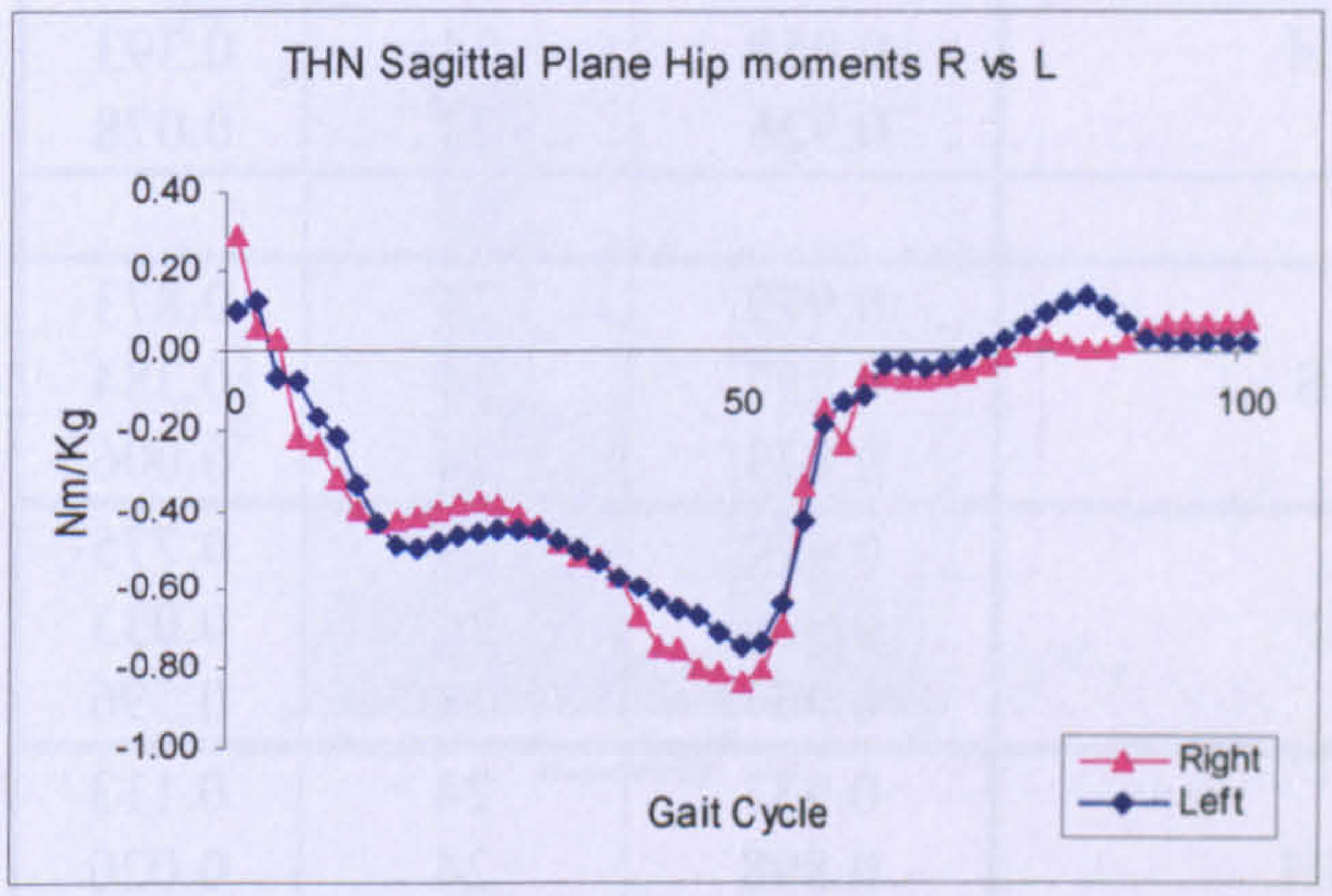
	Sagittal Plane		Frontal Plane		Horizontal Plane	
	Right	Left	Right	Left	Right	Left
0	-0.06	0.02	0.29	0.10	0.02	0.06
2	0.03	0.04	0.06	0.13	0.02	-0.01
4	0.11	0.02	0.04	-0.06	-0.05	-0.04
6	0.21	0.08	-0.21	-0.08	-0.10	-0.11
8	0.32	0.14	-0.23	-0.17	-0.15	-0.15
10	0.42	0.29	-0.31	-0.21	-0.19	-0.20
12	0.47	0.40	-0.39	-0.33	-0.21	-0.22
14	0.48	0.41	-0.43	-0.43	-0.21	-0.21
16	0.45	0.40	-0.42	-0.49	-0.21	-0.18
18	0.38	0.37	-0.41	-0.50	-0.20	-0.15
20	0.36	0.37	-0.40	-0.48	-0.19	-0.14
22	0.32	0.32	-0.38	-0.46	-0.17	-0.12
24	0.28	0.28	-0.37	-0.45	-0.15	-0.11
26	0.24	0.23	-0.38	-0.45	-0.13	-0.10
28	0.23	0.24	-0.40	-0.45	-0.12	-0.08
30	0.26	0.25	-0.43	-0.45	-0.12	-0.07
32	0.28	0.29	-0.47	-0.47	-0.11	-0.07
34	0.29	0.31	-0.51	-0.50	-0.12	-0.07
36	0.32	0.37	-0.52	-0.53	-0.13	-0.08
38	0.35	0.38	-0.57	-0.57	-0.14	-0.09
40	0.39	0.40	-0.67	-0.60	-0.15	-0.10
42	0.41	0.39	-0.75	-0.63	-0.16	-0.11
44	0.42	0.39	-0.76	-0.65	-0.17	-0.12
46	0.40	0.37	-0.80	-0.67	-0.18	-0.14
48	0.28	0.34	-0.81	-0.71	-0.19	-0.15
50	0.13	0.29	-0.83	-0.74	-0.20	-0.15
52	0.00	0.23	-0.80	-0.74	-0.18	-0.12
54	-0.06	0.13	-0.69	-0.64	-0.13	-0.08
56	-0.07	0.03	-0.33	-0.42	-0.07	-0.04
58	-0.07	-0.04	-0.14	-0.18	-0.02	-0.02
60	-0.05	-0.09	-0.23	-0.13	-0.01	-0.02
62	-0.03	-0.08	-0.05	-0.11	0.01	0.00
64	-0.02	-0.04	-0.06	-0.03	0.00	0.00
66	-0.01	-0.01	-0.07	-0.03	0.00	0.00
68	-0.01	0.01	-0.06	-0.04	0.00	0.00
70	-0.01	0.03	-0.06	-0.03	0.00	0.00
72	-0.01	0.04	-0.05	-0.01	0.01	0.00
74	0.00	0.05	-0.03	0.01	0.02	0.01
76	-0.01	0.06	0.00	0.03	0.03	0.01
78	0.00	0.07	0.02	0.07	0.03	0.01
80	0.01	0.07	0.04	0.10	0.04	0.01
82	0.05	0.07	0.02	0.13	0.04	0.00
84	0.08	0.06	0.01	0.14	0.04	-0.01
86	0.08	0.03	0.01	0.12	0.04	-0.01
88	0.07	0.01	0.03	0.08	0.04	-0.01
90	0.05	0.00	0.06	0.04	0.04	-0.01
92	0.03	-0.01	0.08	0.03	0.037	-0.003
94	0.02	-0.01	0.08	0.03	0.024	-0.003
96	0.01	-0.01	0.07	0.03	0.013	-0.002
98	0.00	-0.01	0.08	0.03	0.006	0.001
100	0.02	-0.01	0.09	0.03	0.002	0.001

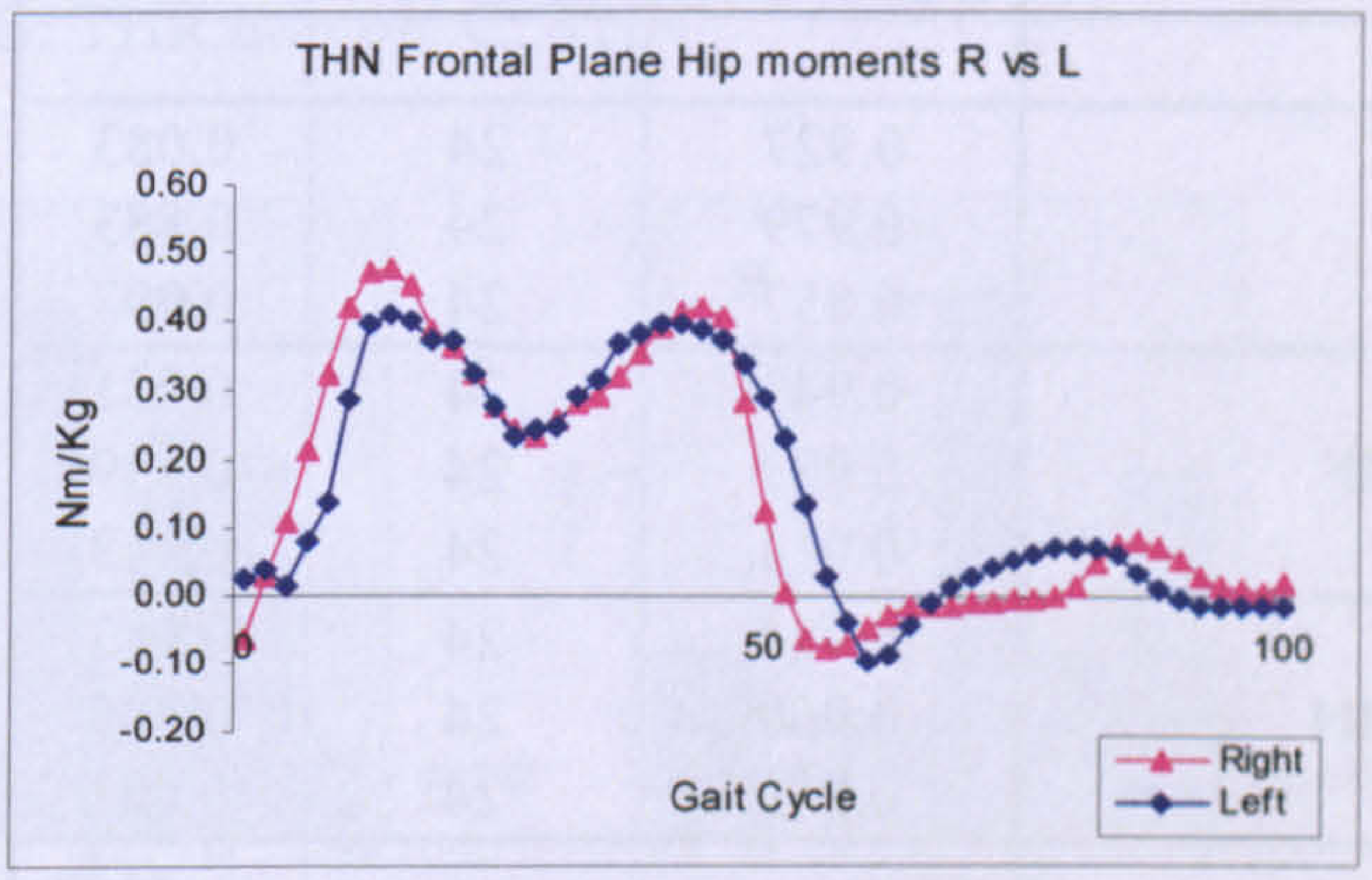
Hip moment, comparison of left and right sided data during walking

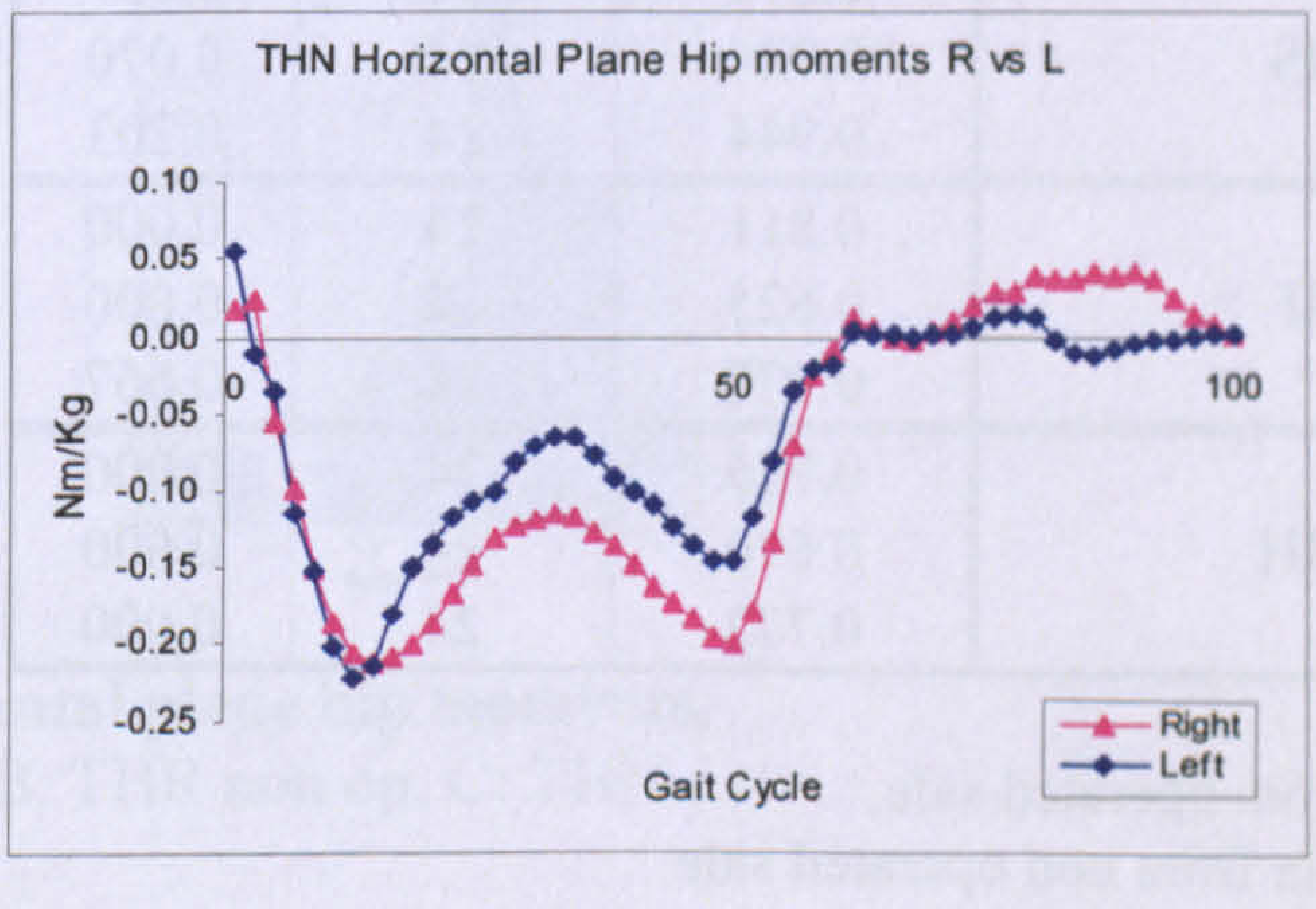
Two sample t-test between THN right and left data sets

	t value	p value
Sagittal	-0.05	0.96
Frontal	-0.26	0.79
Horizontal	-0.65	0.51

No significant difference between right and left data sets for hip moment data for each plane, tested by two sample t-test, significance set at p≤0.05







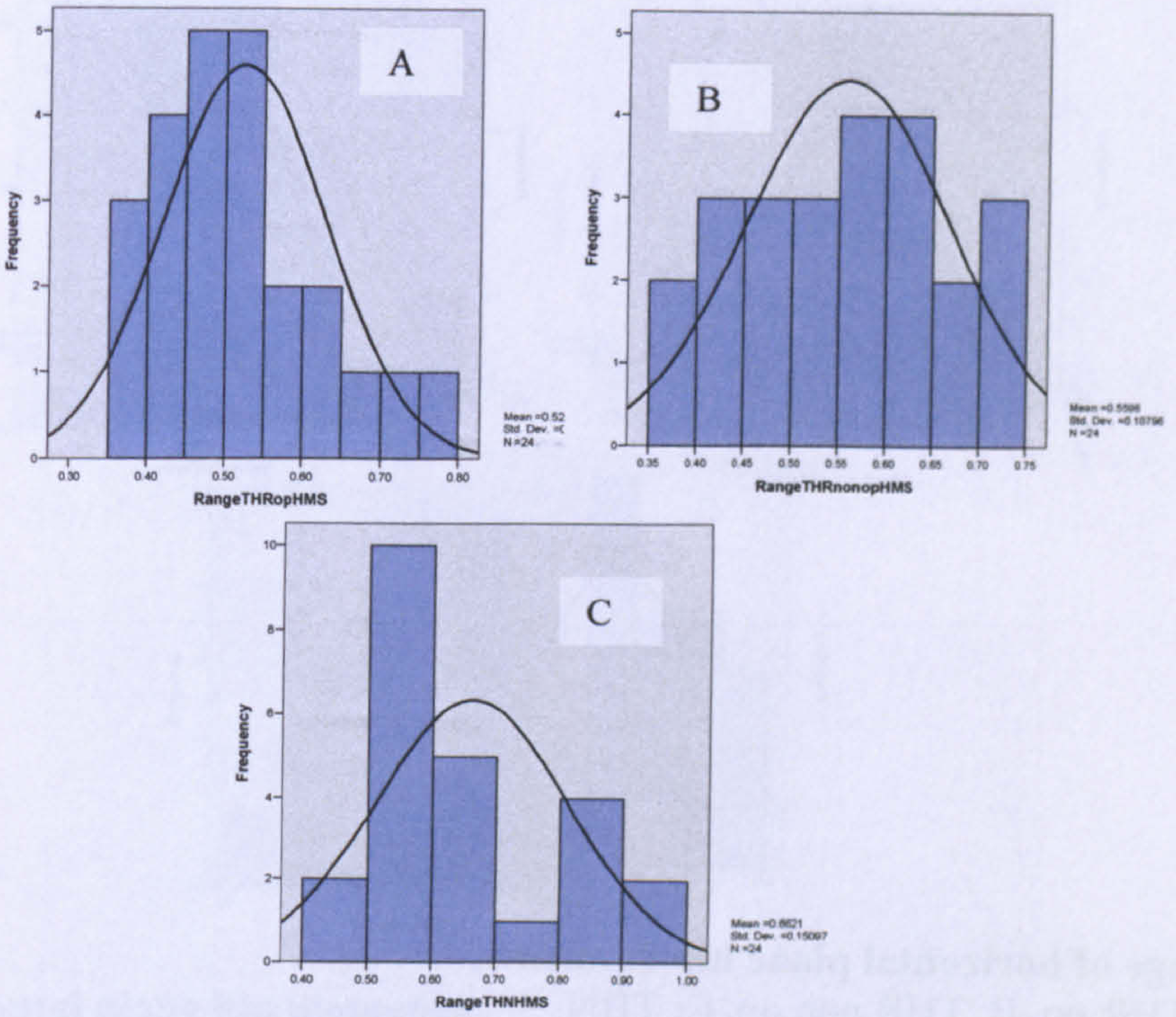
2) Test for Normal Distribution

a) Tests of Normality – Hip Moments

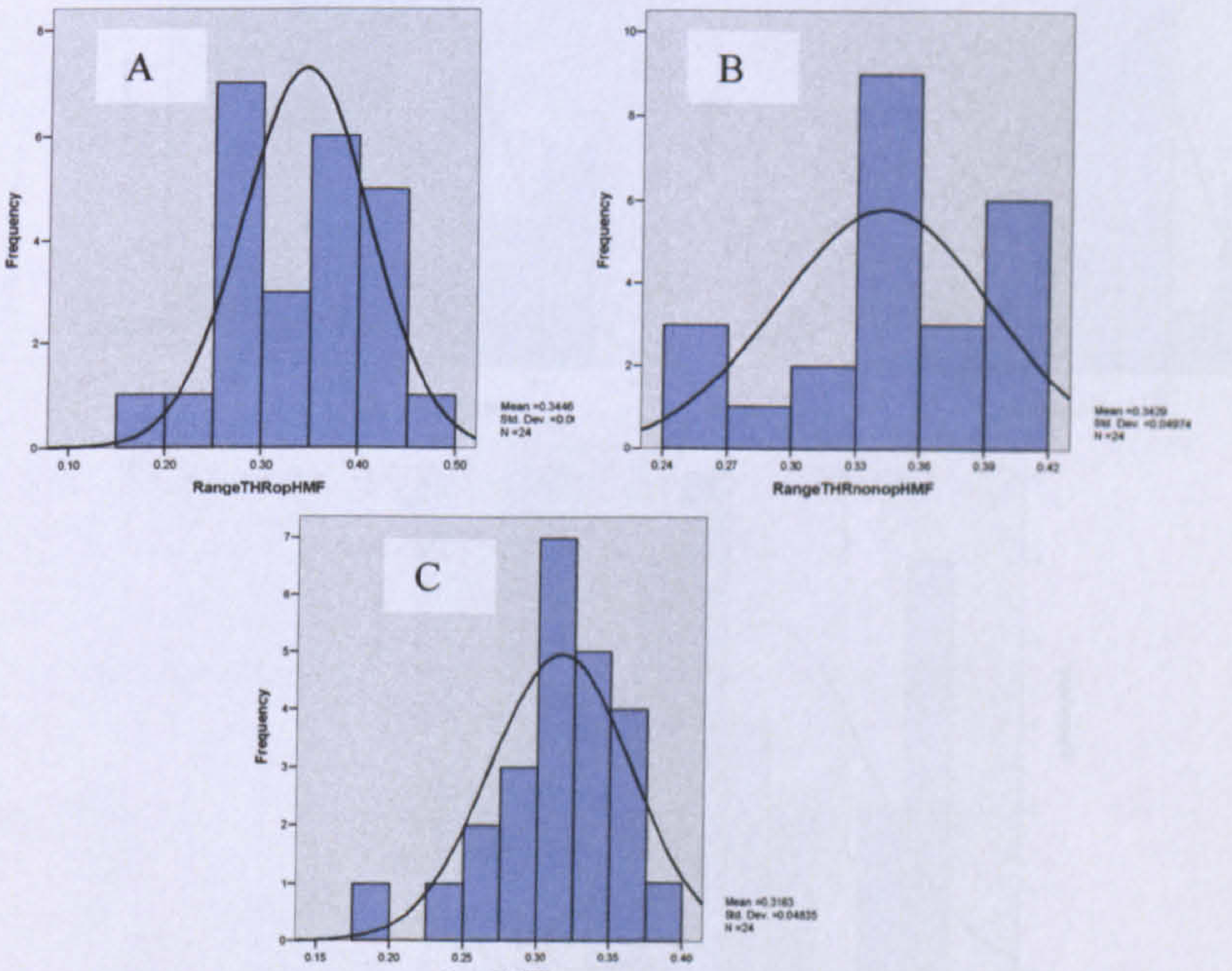
	Shapiro-Wilk		
Range	Statistic	df	Sig.
THR op HMS	0.950	24	0.266
THR nonop HMS	0.955	24	0.343
THN HMS	0.902	24	0.024
THR op HMF	0.972	24	0.727
THR nonop HMF	0.926	24	0.078
THN HMF	0.938	24	0.145
THR op HMH	0.937	24	0.140
THR nonop HMH	0.958	24	0.393
THN HMH	0.926	24	0.078
Peak			
THR op HMS	0.979	24	0.873
THR nonop HMS	0.957	24	0.384
THN HMS	0.873	24	0.006
THR op HMF	0.974	24	0.775
THR nonop HMF	0.909	24	0.033
THN HMF	0.967	24	0.596
THR op HMH	0.933	24	0.113
THR nonop HMH	0.898	24	0.020
THN HMH	0.848	24	0.002
Heel Strike			
THR op HMS	0.927	24	0.083
THR non HMS	0.979	24	0.883
THN HMS	0.857	24	0.003
THR op HMF	0.949	24	0.251
THR nonop HMF	0.937	24	0.139
THN HMF	0.914	24	0.043
THR op HMH	0.984	24	0.953
THR nonop HMH	0.960	24	0.435
THN HMH	0.836	24	0.001
Toe off			
THR op HMS	0.876	24	0.007
THR nonop HMS	0.924	24	0.070
THN HMS	0.944	24	0.203
THR op HMF	0.811	24	0.000
THR nonop HMF	0.625	24	0.000
THN HMF	0.970	24	0.667
THR op HMH	0.775	24	0.000
THR nonop HMH	0.670	24	0.000
THN HMH	0.772	24	0.000

THR op – data from operated side,
THR non op - data from non operated side
THN - data from control participants,
HMS – Hip movement in Sagittal Plane,
HMF – Hip movement in Frontal Plane,
HMH - Hip movement in Horizontal Plane

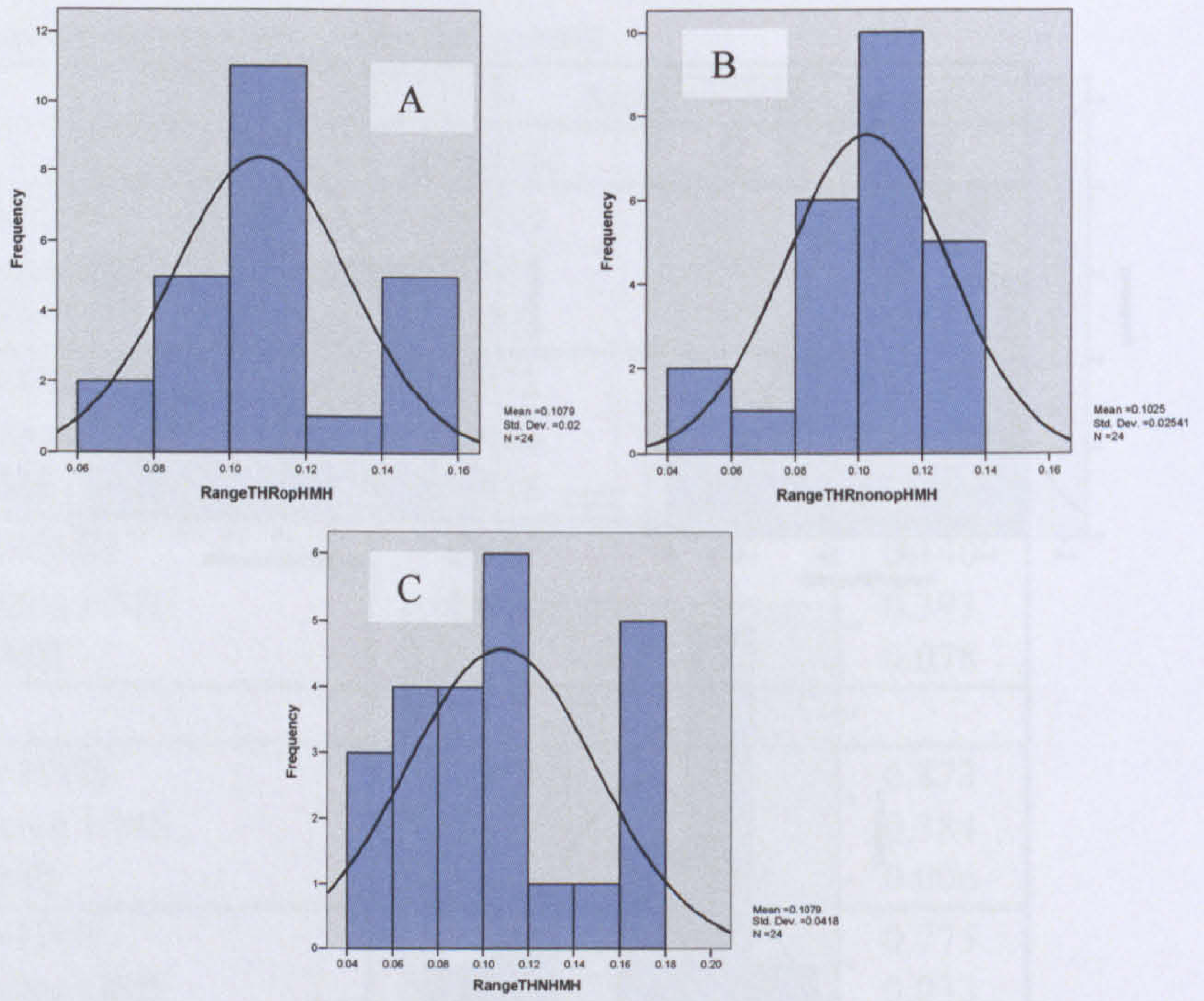
b) Normal Distribution plots



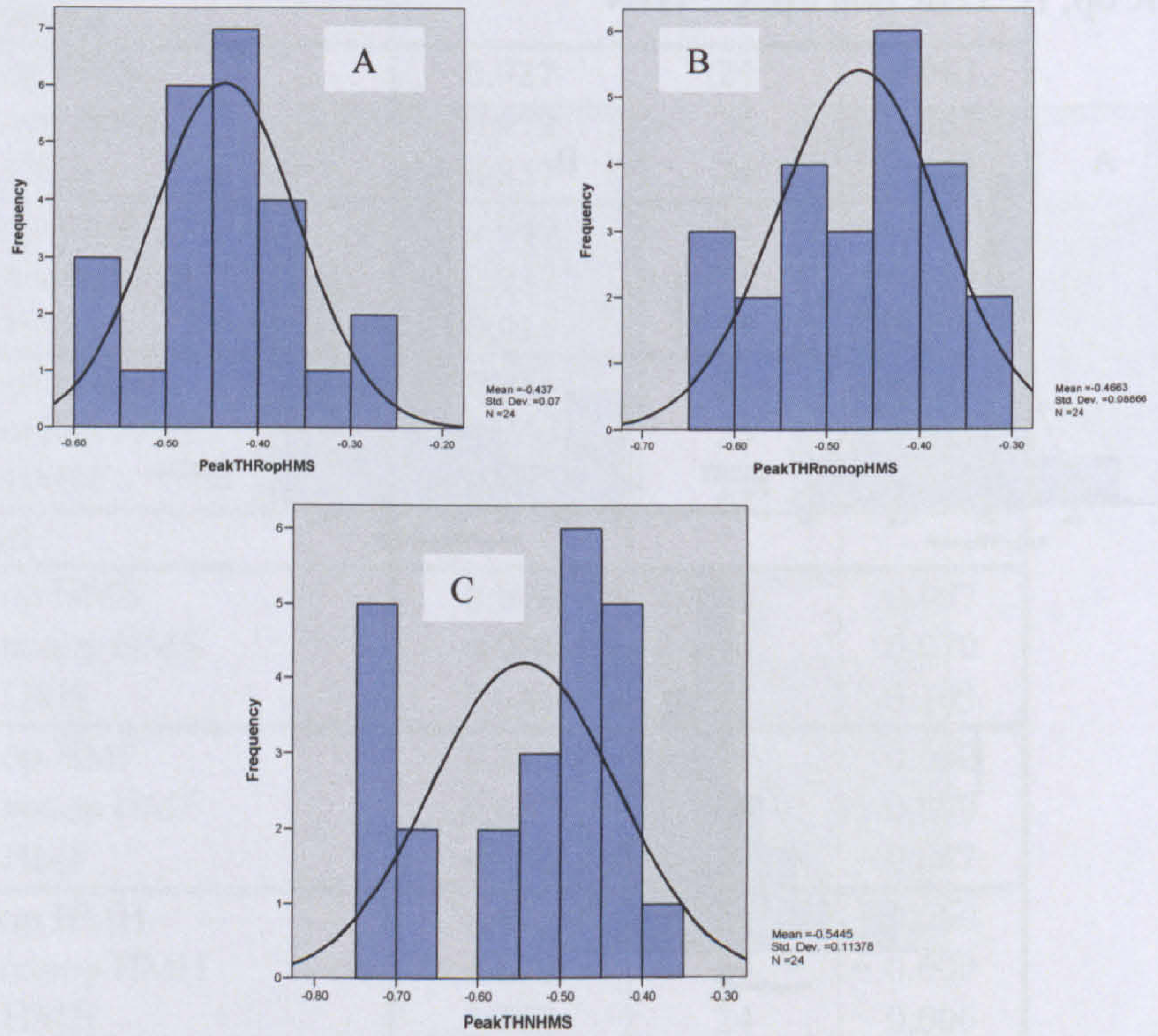
Range of sagittal plane hip moments
A: THR op, B: THR non op, C: THN



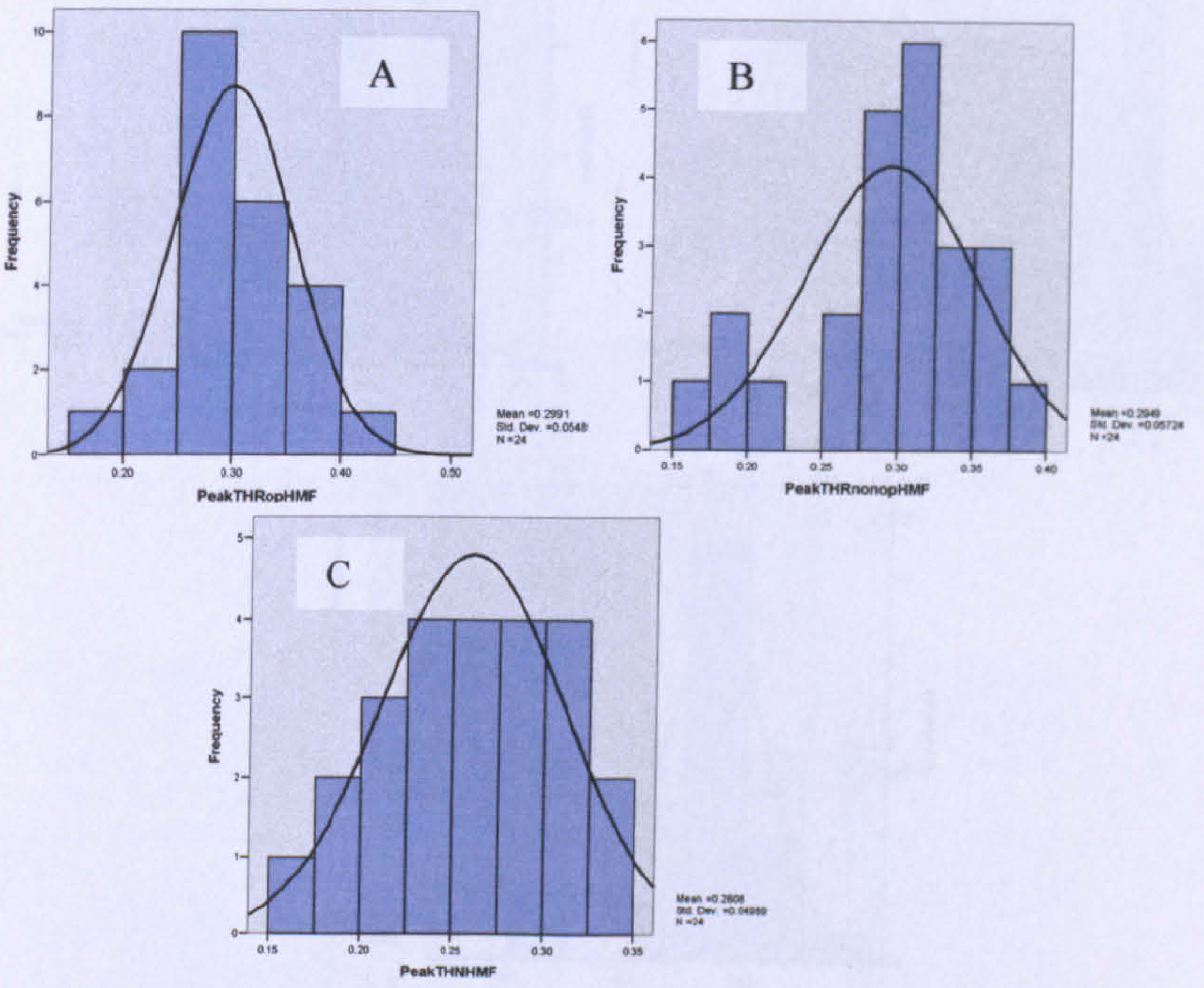
Range of frontal plane hip moments,
A: THR op, B: THR non op, C: THN



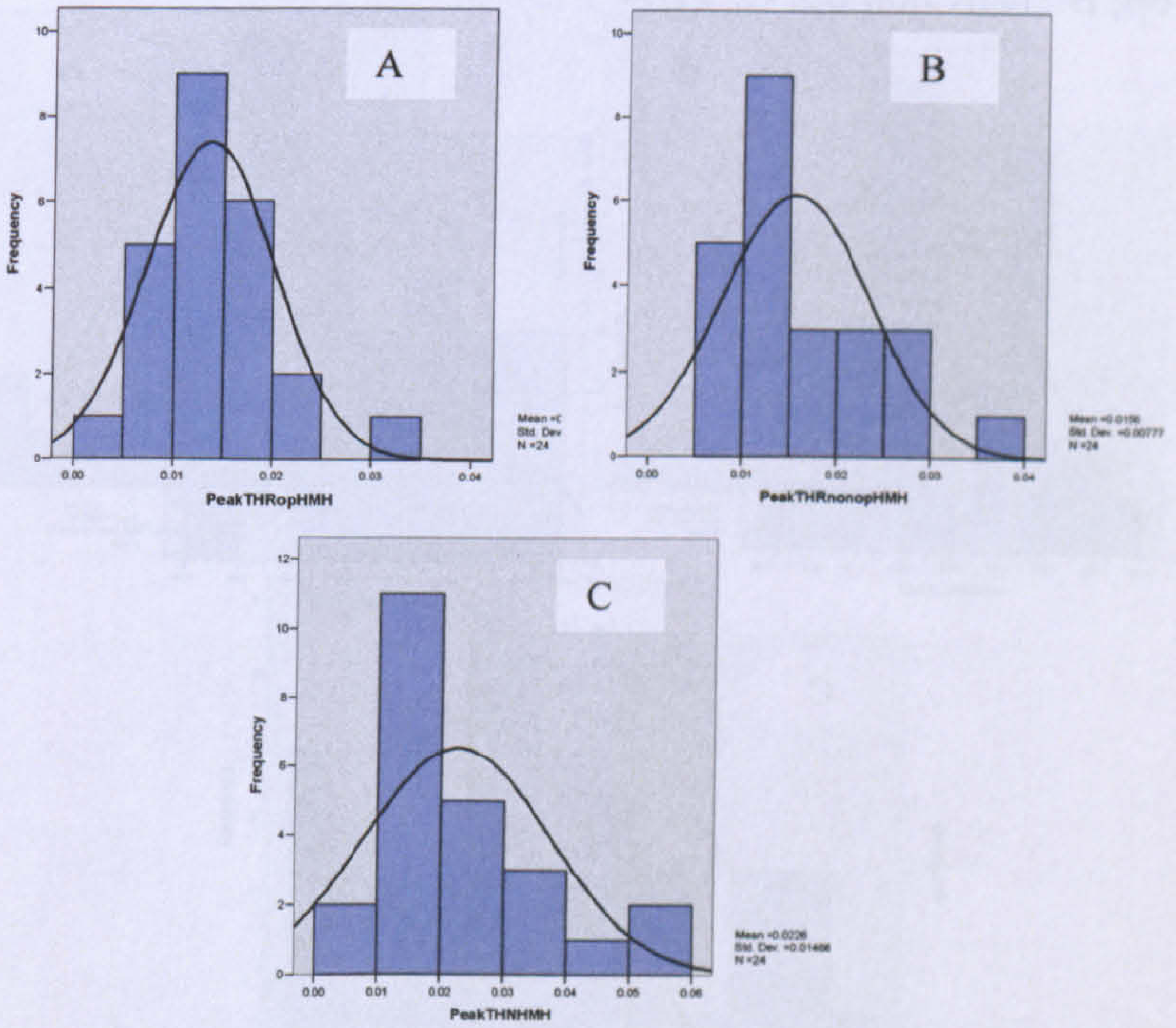
Range of horizontal plane hip moments,
A: THR op, B: THR non op, C: THN



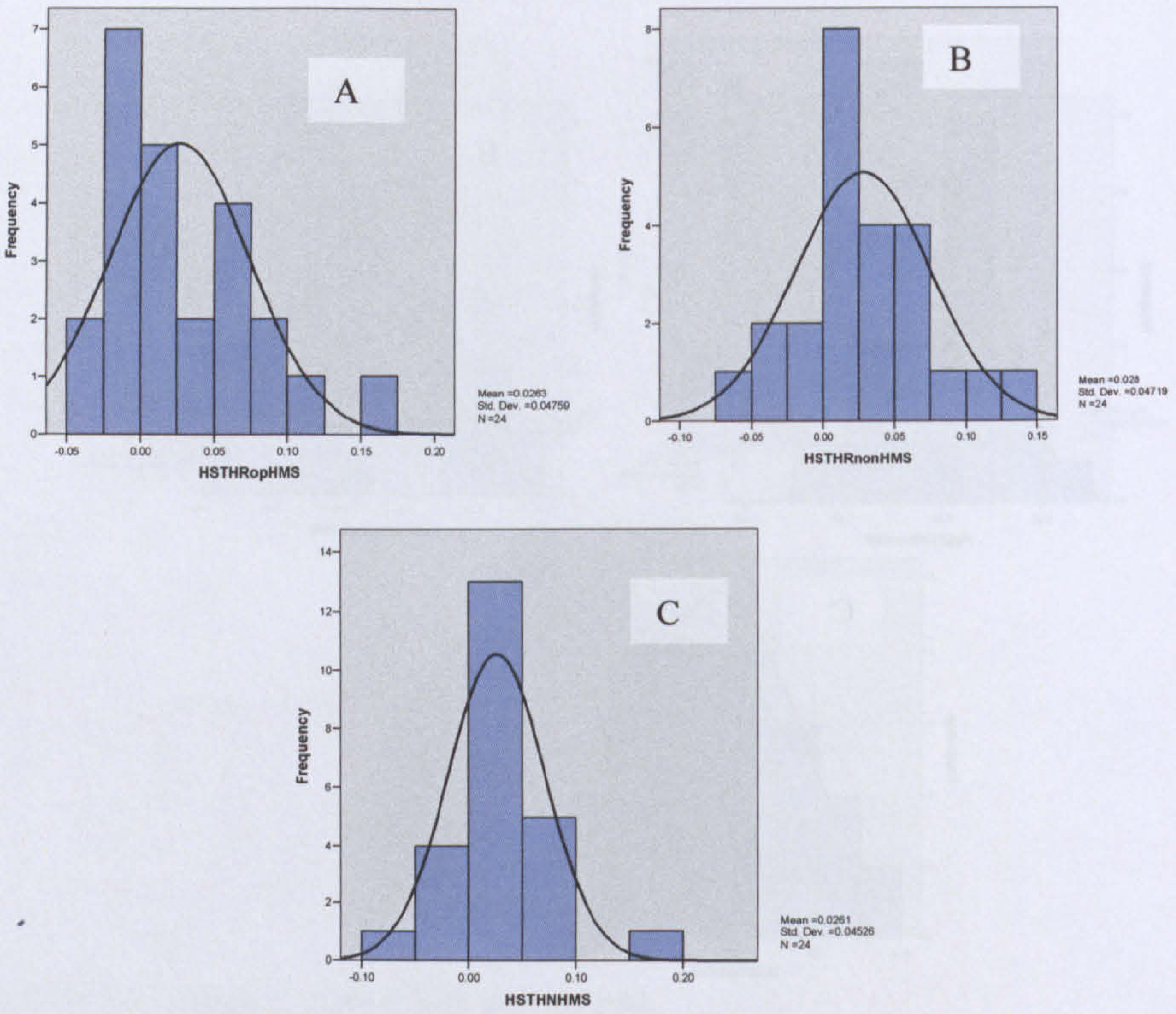
Peak sagittal plane hip moments
A: THR op, B: THR non op, C: THN



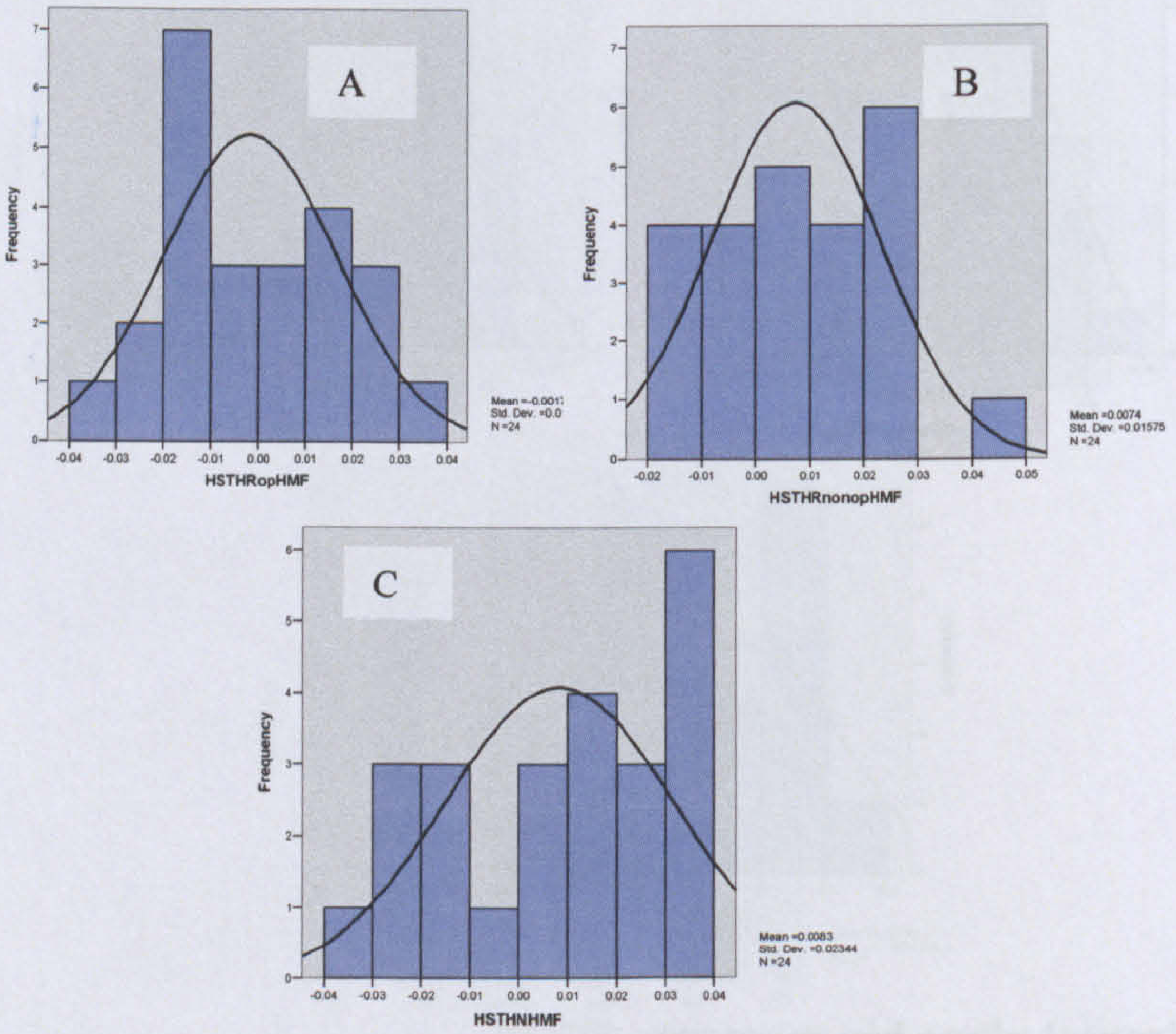
Peak frontal plane hip moments,
A: THR op, B: THR non op, C: THN



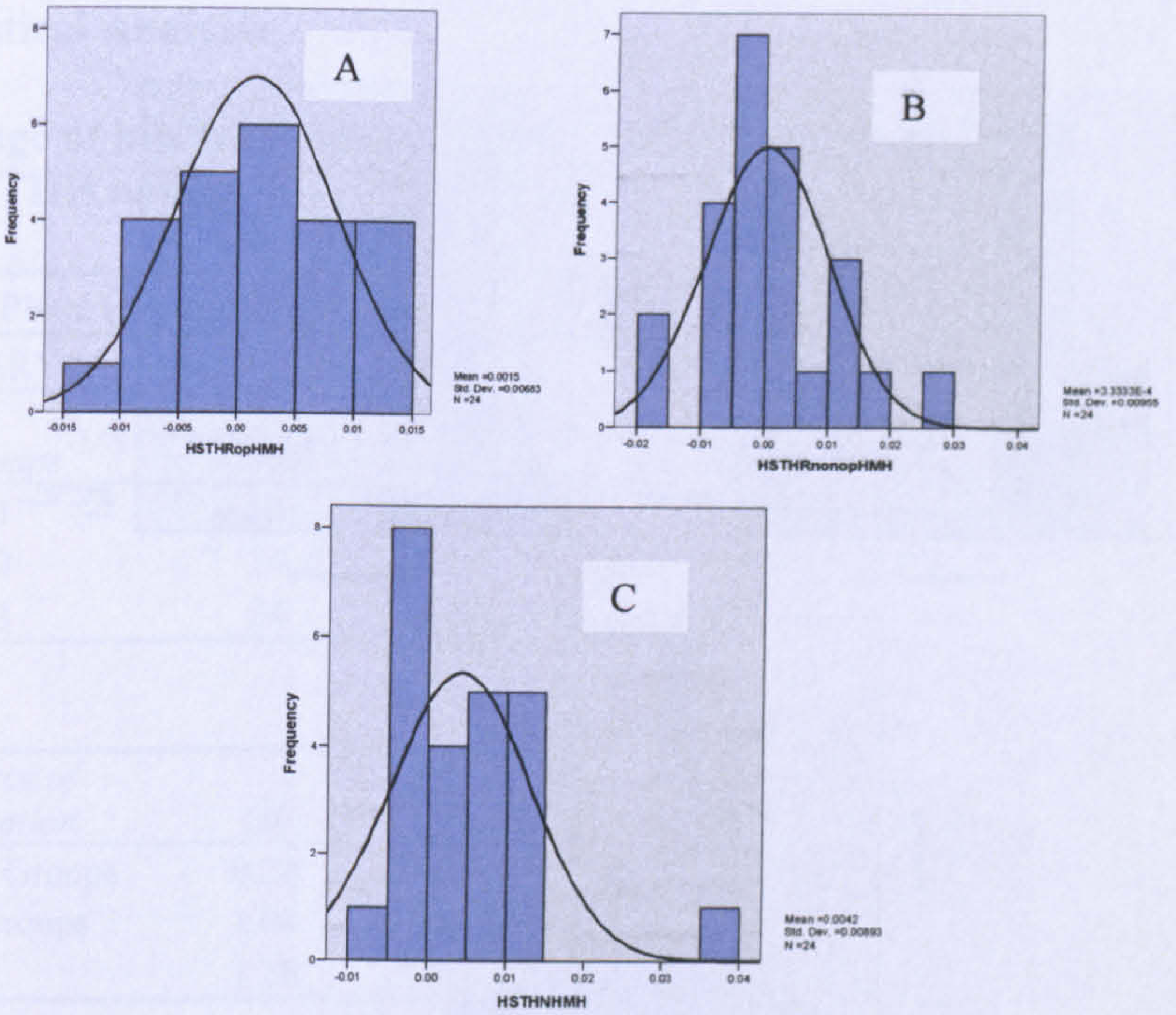
Peak horizontal plane hip moments,
A: THR op, B: THR non op, C: THN



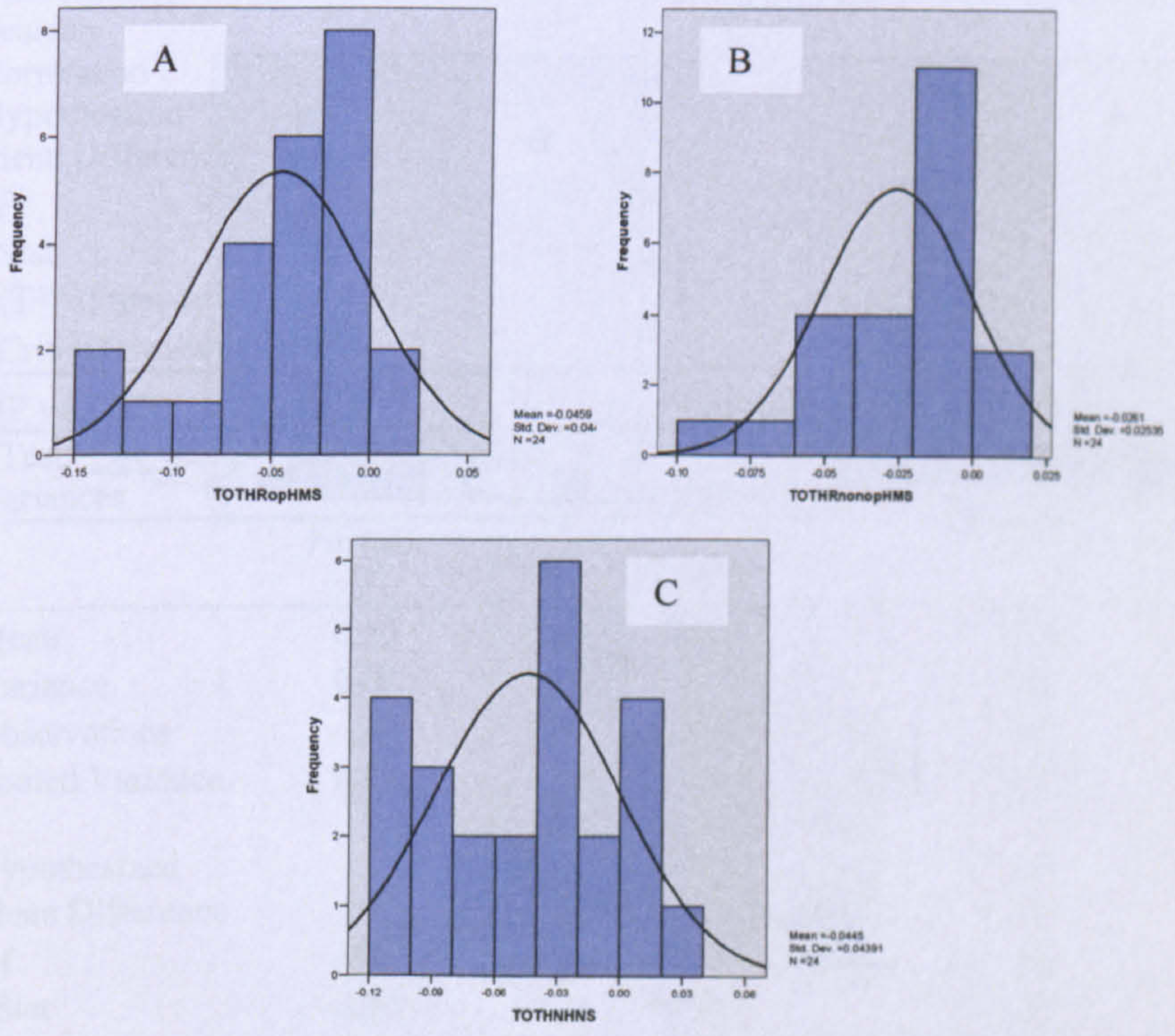
Sagittal plane hip moments at heel strike,
A: THR op, B: THR non op, C: THN



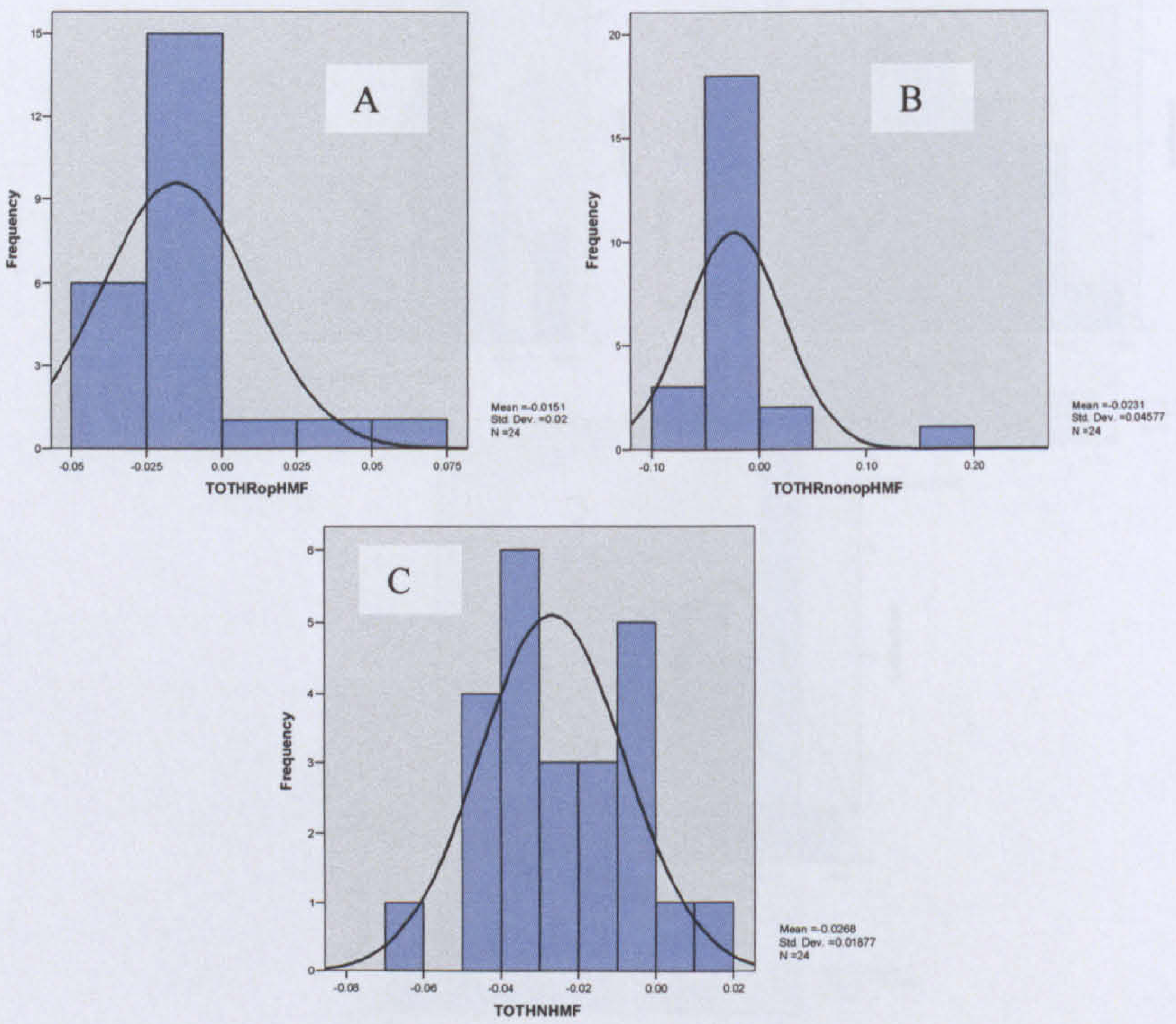
Frontal plane hip moments at heel strike,
A: THR op, B: THR non op, C: THN



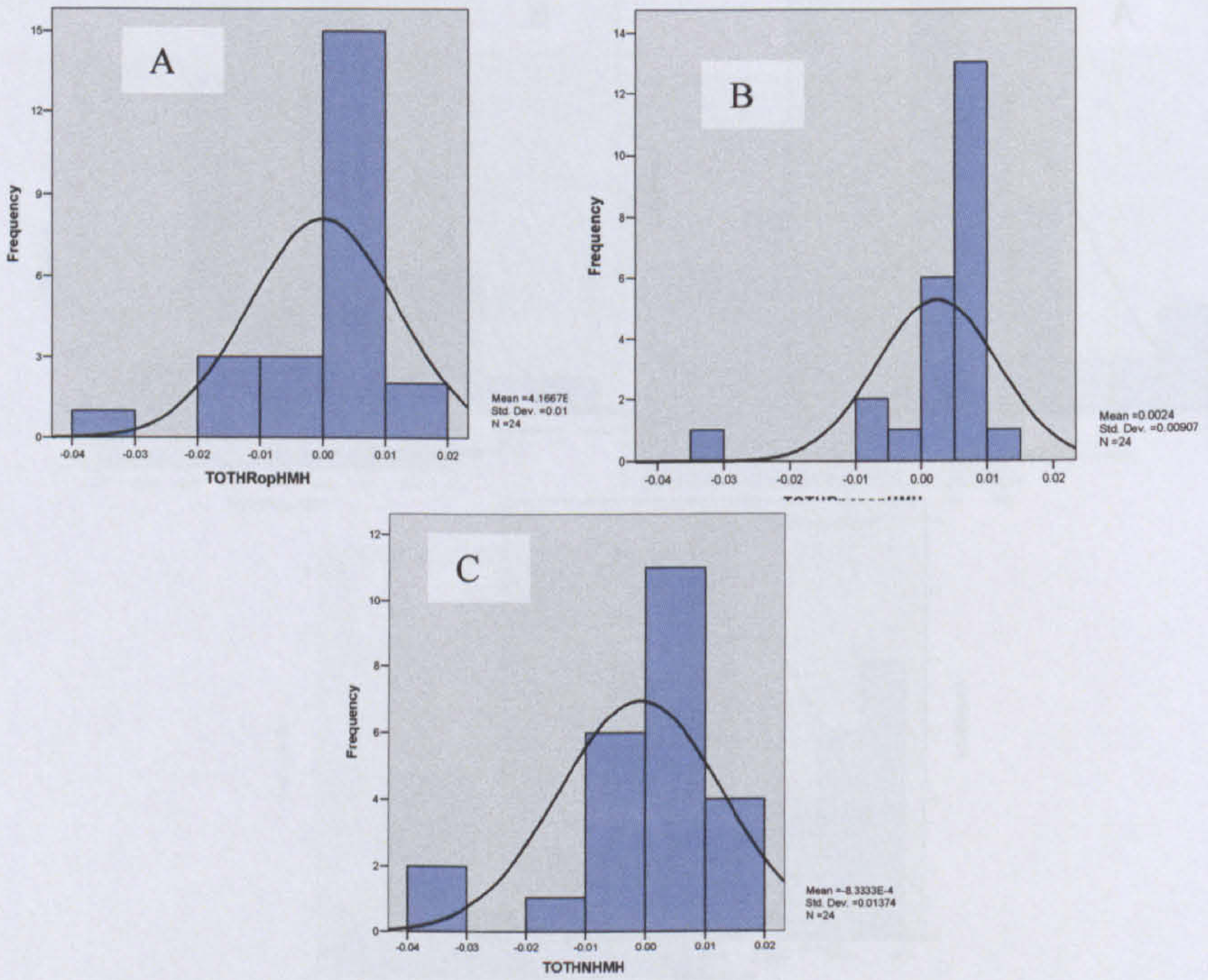
Horizontal plane hip moments at heel strike,
A: THR op, B: THR non op, C: THN



Sagittal plane hip moments at toe off,
A: THR op, B: THR non op, C: THN



Frontal plane hip moments at toe off,
A: THR op, B: THR non op, C: THN



Horizontal plane hip moments at toe off,
A: THR op, B: THR non op, C: THN

3) Statistical Analysis

a) Range of hip moments: One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Sagittal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	12.62	0.53	0.01
Column 2	24	13.44	0.56	0.01
Column 3	24	15.89	0.66	0.02

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.24	2	0.12	8.06	0.0007	3.13
Within Groups	1.04	69	0.02			
Total	1.28	71				

OP vs Non op

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.53	0.56
Variance	0.01	0.01
Observations	24	24
Pearson Correlation	0.03	
Hypothesized Mean Difference	0	
df	23	
t Stat	-1.13	
P(T<=t) two-tail	0.27	
t Critical two-tail	2.07	

OP vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	0.53	0.67
Variance	0.01	0.02
Observations	24	24
Pooled Variance	0.02	
Hypothesized Mean Difference	0	
Df	46	
t Stat	-3.65	
P(T<=t) two-tail	0.0007	
t Critical two-tail	2.01	

Non op vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	0.56	0.66
Variance	0.01	0.02
Observations	24	24
Pooled Variance	0.02	
Hypothesized Mean Difference	0	
df	46	
t Stat	-2.71	
P(T<=t) two-tail	0.009	
t Critical two-tail	2.01	

Frontal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	8.29	0.35	0.004
Column 2	24	8.24	0.34	0.003
Column 3	24	7.57	0.32	0.002

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.01	2	0.007	2.25	0.11	3.13
Within Groups	0.21	69	0.003			
Total	0.22	71				

Horizontal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	2.59	0.11	0.0005
Column 2	24	2.46	0.10	0.0007
Column 3	24	2.60	0.11	0.0017

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0005	2	0.0003	0.27	0.76	3.13
Within Groups	0.067	69	0.001			
Total	0.067	71				

b) Peak hip moments: One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Sagittal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-10.49	-0.44	0.006
Column 2	24	-11.19	-0.47	0.008
Column 3	24	-13.07	-0.55	0.013

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.15	2	0.07	8.21	0.0006	3.13
Within Groups	0.62	69	0.009			
Total	0.77	71				

OP vs Non op

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	-0.44	-0.47
Variance	0.006	0.008
Observations	24	24
Pearson Correlation	-0.07	
Hypothesized Mean Difference	0	
df	23	
t Stat	1.17	
P(T<=t) two-tail	0.25	
t Critical two-tail	2.07	

OP vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	-0.44	-0.54
Variance	0.006	0.013
Observations	24	24
Pooled Variance	0.01	
Hypothesized Mean Difference	0	
df	46	
t Stat	3.80	
P(T<=t) two-tail	0.0004	
t Critical two-tail	2.01	

Non op vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	-0.47	-0.54
Variance	0.008	0.01
Observations	24	24
Pooled Variance	0.01	
Hypothesized Mean Difference	0	
df	46	
t Stat	2.65	
P(T<=t) two-tail	0.011	
t Critical two-tail	2.01	

Frontal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	7.18	0.29	0.003
Column 2	24	7.08	0.29	0.003
Column 3	24	6.26	0.26	0.003

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.02	2	0.01	3.63	0.032	3.13
Within Groups	0.20	69	0.003			
Total	0.22	71				

OP vs Non op

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.29	0.29
Variance	0.003	0.003
Observations	24	24
Pearson Correlation	0.23	
Hypothesized Mean Difference	0	
df	23	
t Stat	0.29	
P(T<=t) two-tail	0.77	
t Critical two-tail	2.07	

OP vs THN			**Non op vs THN**		
t-Test: Two-Sample Assuming Equal Variances			t-Test: Two-Sample Assuming Equal Variances		
	Variable 1	*Variable 2*		*Variable 1*	*Variable 2*
Mean	0.29	0.26	Mean	0.29	0.26
Variance	0.003	0.003	Variance	0.003	0.003
Observations	24	24	Observations	24	24
Pooled Variance	0.003		Pooled Variance	0.003	
Hypothesized Mean Difference	0		Hypothesized Mean Difference	0	
df	46		df	46	
t Stat	2.53		t Stat	2.21	
P(T<=t) two-tail	0.015		P(T<=t) two-tail	0.033	
t Critical two-tail	2.01		t Critical two-tail	2.01	

Horizontal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	0.33	0.01	0.00004
Column 2	24	0.37	0.02	0.00006
Column 3	24	0.55	0.02	0.0002

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001	2	0.0006	5.19	0.008	3.13
Within Groups	0.007	69	0.0001			
Total	0.008	71				

OP vs Non op

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.014	0.02
Variance	0.00004	0.00006
Observations	24	24
Pearson Correlation	0.084	
Hypothesized Mean Difference	0	
df	23	
t Stat	-0.93	
P(T<=t) two-tail	0.36	
t Critical two-tail	2.07	

OP vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	0.01	0.02
Variance	0.00004	0.0002
Observations	24	24
Pooled Variance	0.0001	
Hypothesized Mean Difference	0	
df	46	
t Stat	-2.77	
P(T<=t) two-tail	0.008	
t Critical two-tail	2.01	

Non op vs THN

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	0.02	0.02
Variance	0.00006	0.0002
Observations	24	24
Pooled Variance	0.0001	
Hypothesized Mean Difference	0	
df	46	
t Stat	-2.13	
P(T<=t) two-tail	0.039	
t Critical two-tail	2.01	

c) Hip moments at Heel strike: One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Sagittal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	0.63	0.03	0.002
Column 2	24	0.67	0.03	0.002
Column 3	24	0.63	0.03	0.002

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00005	2	0.00002	0.01	0.99	3.13
Within Groups	0.15	69	0.002			
Total	0.15	71				

Frontal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-0.04	-0.002	0.0003
Column 2	24	0.18	0.007	0.0002
Column 3	24	0.20	0.008	0.0006

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.002	2	0.0008	1.98	0.15	3.13
Within Groups	0.03	69	0.0004			
Total	0.03	71				

Horizontal Plane Hip moments Anova: Single Factor

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	0.036	0.002	0.00004
Column 2	24	0.005	0.0002	0.00009
Column 3	24	0.10	0.004	0.00007

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0002	2	0.0001	1.39	0.255	3.13
Within Groups	0.005	69	0.00007			
Total	0.005	71				

d) Hip moments at Toe Off: One way ANOVA between the groups (THR op, THR nonop, THN), with post hoc t-tests where appropriate

Sagittal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-1.1	-0.05	0.002
Column 2	24	-0.63	-0.03	0.0006
Column 3	24	-1.069	-0.05	0.002

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.006	2	0.003	1.91	0.16	3.13
Within Groups	0.11	69	0.002			
Total	0.11	71				

Frontal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-0.36	-0.02	0.0006
Column 2	24	-0.56	-0.02	0.002
Column 3	24	-0.65	-0.03	0.0003

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.002	2	0.0009	0.85	0.43	3.13
Within Groups	0.07	69	0.001			
Total	0.07	71				

Horizontal Plane Hip moments Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	24	-0.003	-0.0001	0.0001
Column 2	24	0.05	0.002	0.00007
Column 3	24	-0.02	-0.0008	0.0002

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0001	2	0.00005	0.45	0.64	3.13
Within Groups	0.009	69	0.0001			
Total	0.009	71				

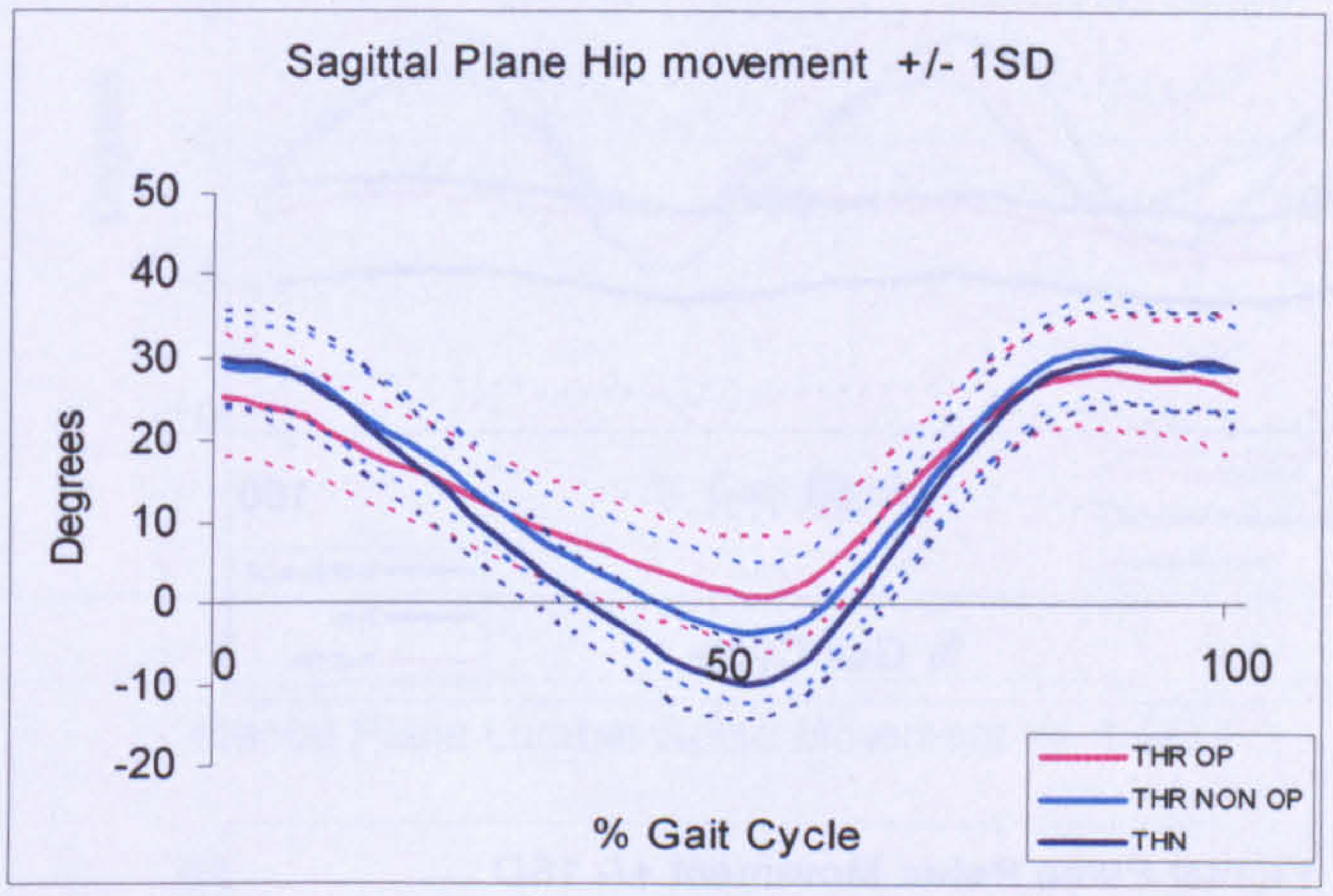
Appendix W: Stance and Swing times

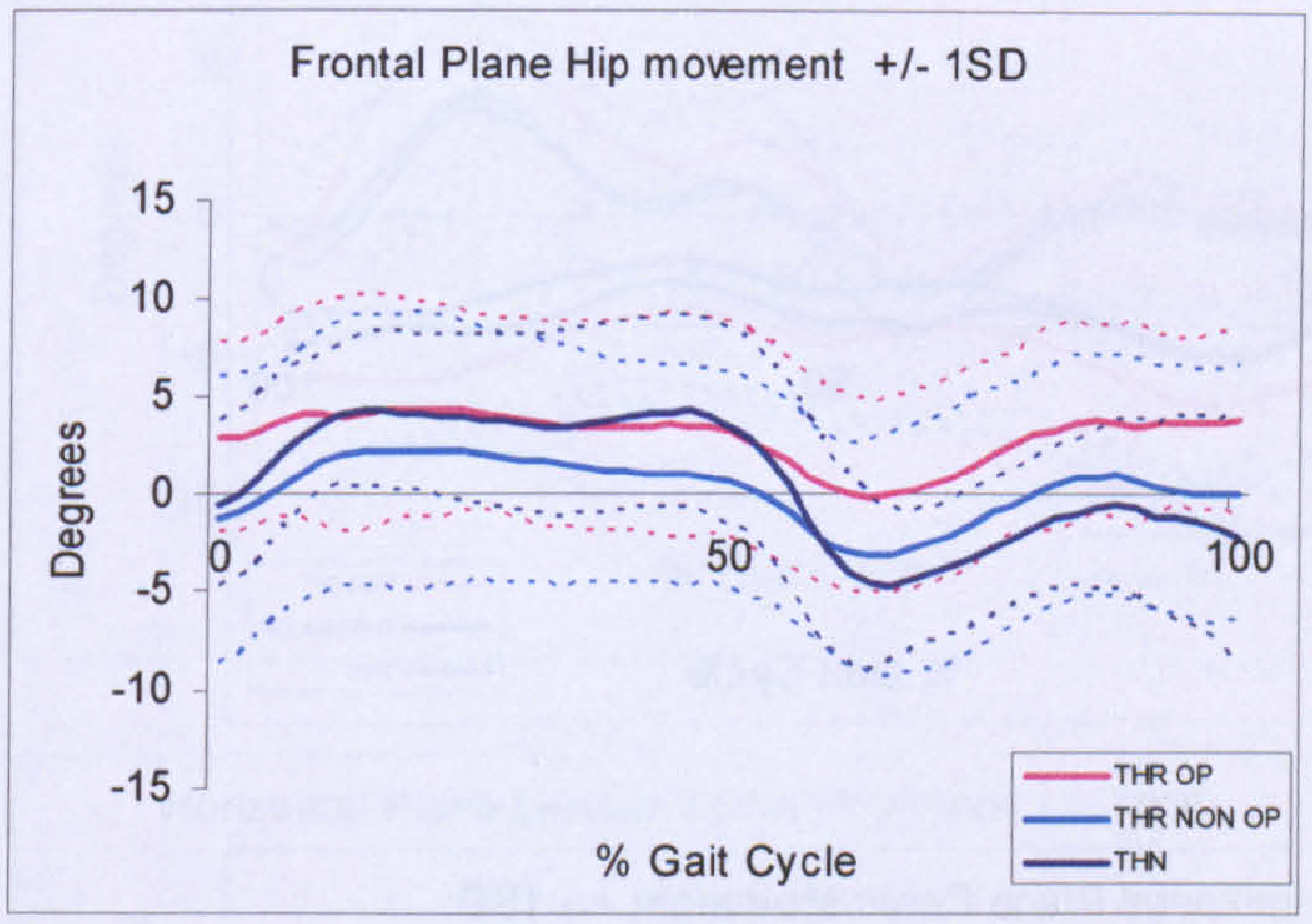
a) Raw data % stance and swing times (%)

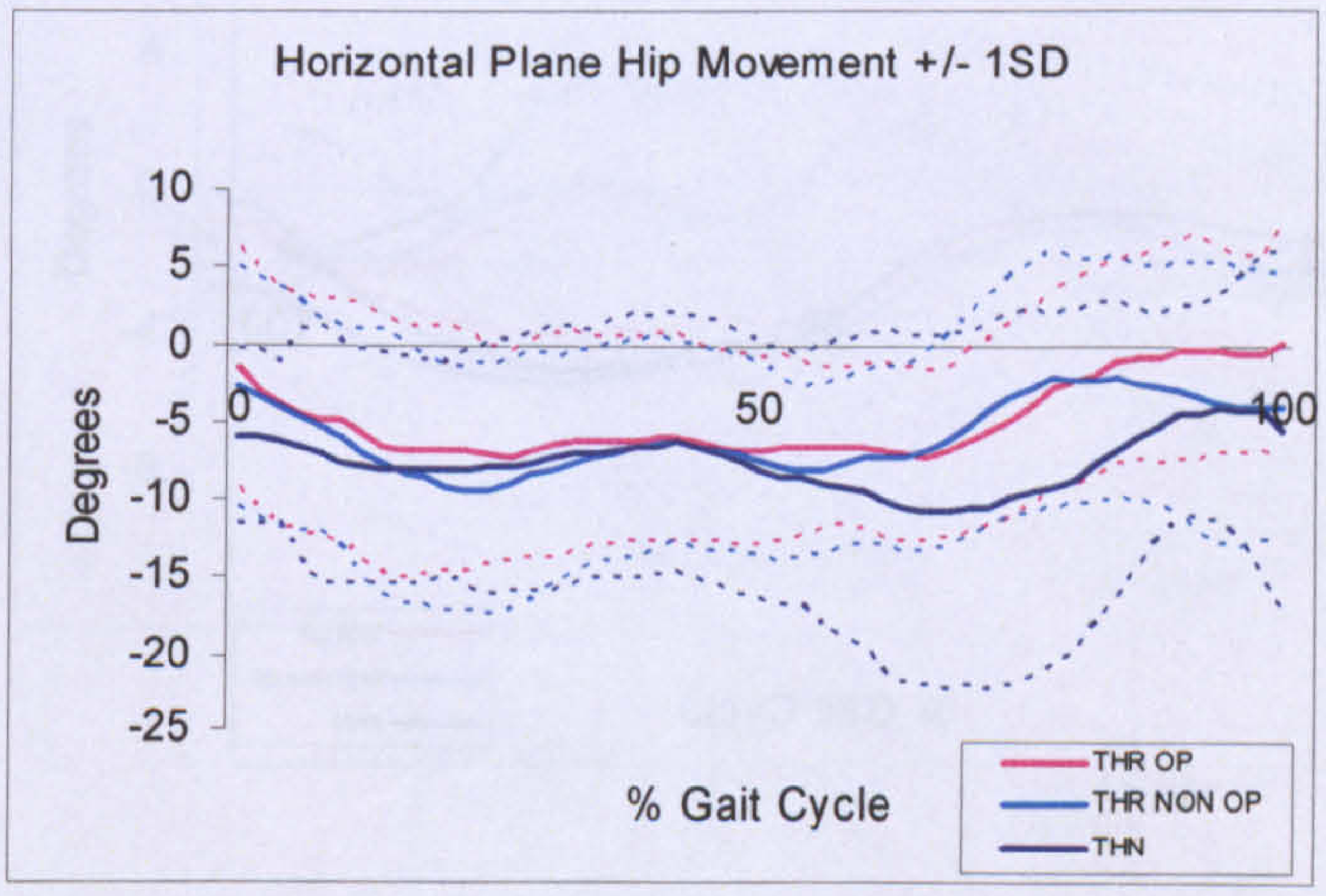
	Stance (%)				Swing (%)			
	THR		THN		THR		THN	
	Left	Right	Left	Right	Left	Right	Left	Right
	66.58	66.58	60.78	61.32	33.42	33.42	39.22	38.68
	64.14	66.75	60.72	61.90	35.86	33.25	39.28	38.10
	64.44	65.90	64.06	65.88	35.56	34.10	35.94	34.12
	69.30	68.31	63.34	62.05	30.70	31.69	36.66	37.95
	57.59	61.41	60.65	67.09	42.41	38.59	39.35	32.91
	61.37	61.54	63.43	63.59	38.63	38.46	36.57	36.41
	67.40	62.52	62.80	56.56	32.60	37.48	37.20	43.44
	64.47	62.30	61.89	60.43	35.53	37.70	38.11	39.57
	58.62	66.86	59.75	56.11	41.38	33.14	40.25	43.89
	59.18	62.33	58.78	57.01	40.82	37.67	41.22	42.99
	67.46	67.46	63.54	73.47	32.54	32.54	36.46	26.53
	65.92	62.75	58.27	62.37	34.08	37.25	41.73	37.63
	61.11	62.18	62.67	63.81	38.89	37.82	37.33	36.19
	65.82	63.15	61.78	63.31	34.18	36.85	38.22	36.69
	61.92	61.11	63.25	60.07	38.08	38.89	36.75	39.93
	66.89	66.87	64.61	59.86	33.11	33.13	35.39	40.14
	63.70	61.65	56.10	63.93	36.30	38.35	43.90	36.07
	62.40	61.36	62.67	69.16	37.60	38.64	37.33	30.84
	61.33	54.48	65.20	61.27	38.67	45.52	34.80	38.73
	62.26	60.85	62.64	62.51	37.74	39.15	37.36	37.49
	62.71	63.07	60.78	60.78	37.29	36.93	39.22	39.22
	62.12	64.37	61.48	62.07	37.88	35.63	38.52	37.93
	65.44	66.26	64.14	64.62	34.56	33.74	35.86	35.38
	63.72	51.20	61.21	60.05	36.28	48.80	38.79	39.95
Mean	63.57	63.48	61.86	62.47	36.43	36.52	38.14	37.53
SD	3.04	3.11	2.15	3.86	3.04	3.11	2.15	3.86

Appendix X: Group variation in all three planes

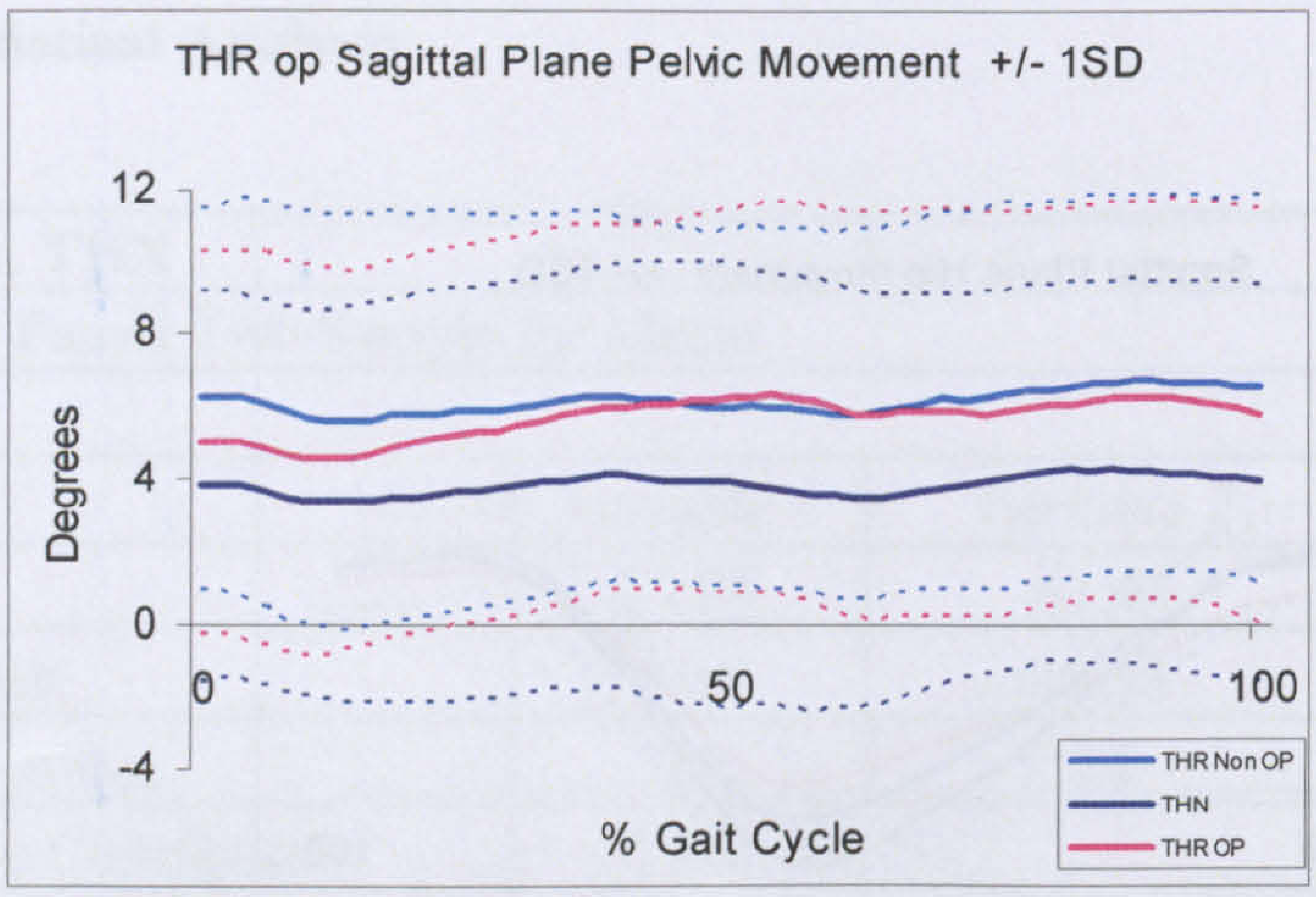
Hip

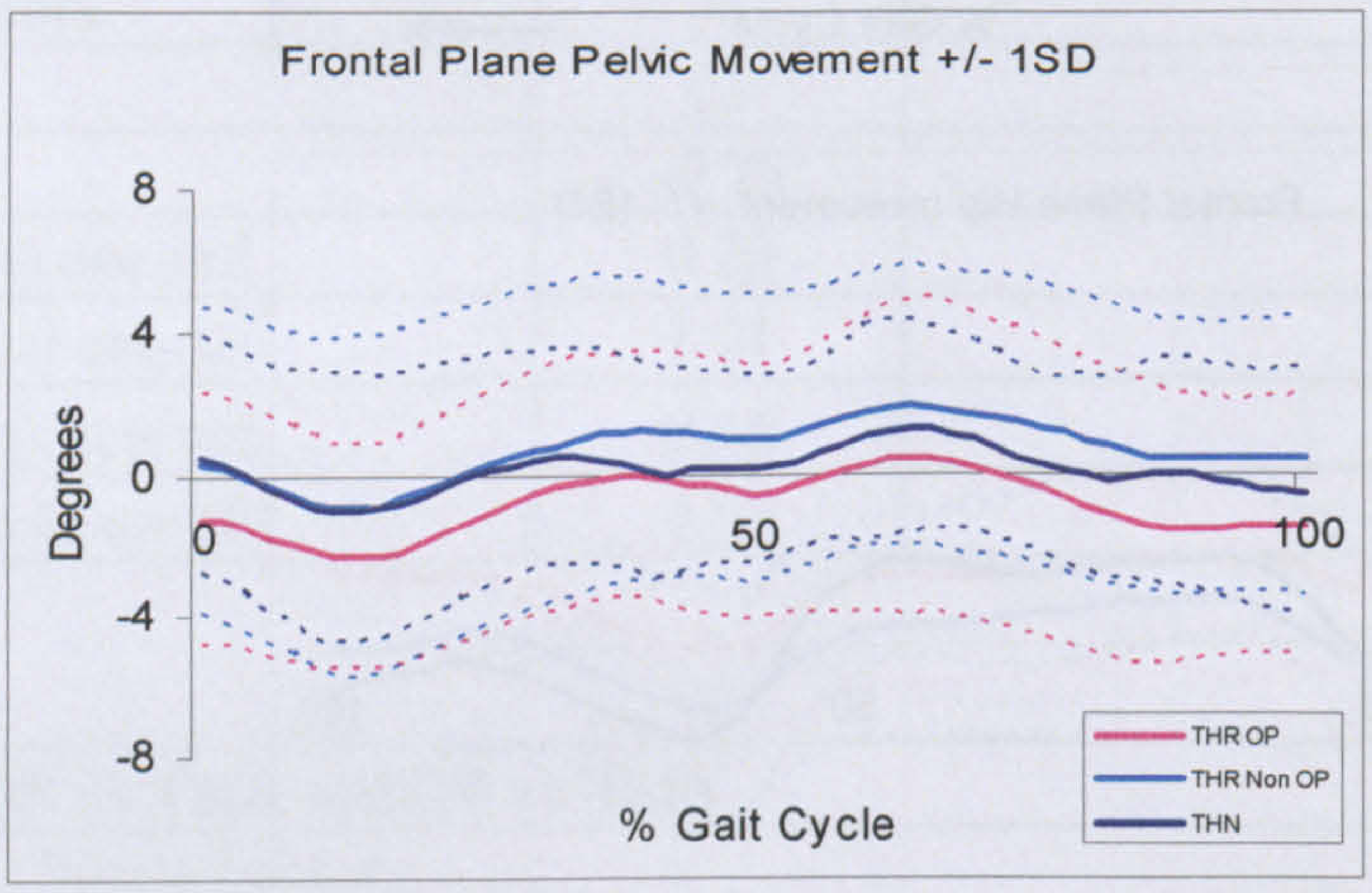


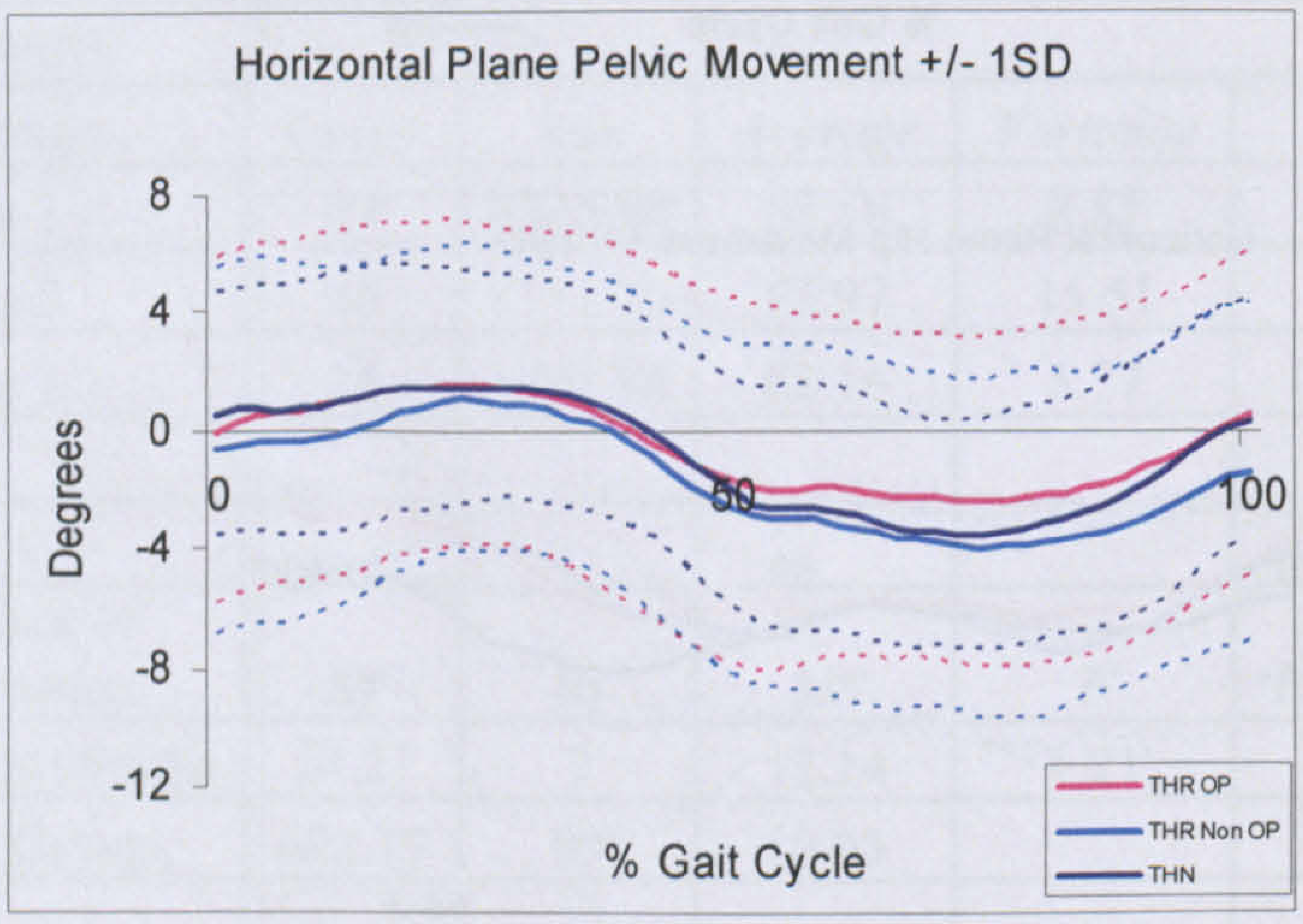




Pelvis


THR op Sagittal Plane Pelvic Movement +/- 1SD
12
8
4
0
-4
Degrees
0
50
100
% Gait Cycle
THR Non OP
THN
THR OP


Frontal Plane Pelvic Movement +/- 1SD
8
4
0
-4
-8
Degrees
0
50
100
% Gait Cycle
THR OP
THR Non OP
THN


Horizontal Plane Pelvic Movement +/- 1SD
8
4
0
-4
-8
-12
Degrees
0
50
100
% Gait Cycle
THR OP
THR Non OP
THN

Lumbar Spine