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Pelvic tilt and Anterior Pelvic Plane inclination in normal individuals between different postures of daily life

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ABSTRACT

Pelvic tilt is known to affect the functional outcome of total hip arthroplasty. Postural changes in individual pelvic tilt can greatly alter the final orientation of the acetabular cup from the surgeon's expectations. This affects bearing surface performance, potentially resulting in impingement and dislocation. Predicting change in pelvic tilt and accounting for its effect remains a problem in navigated surgery.

This study measured 12 healthy individuals in standing, seated, supine and lateral decubitus position, using Vicon motion capture. The standard pelvic tilt, as defined by the ISB, and the sagittal inclination angle of the anterior pelvic plane (APP) were measured independently. We documented postural changes in pelvic tilt and examined gender differences and the relationship between APP-inclination and ISB-defined pelvic tilt.

It was found that, in standing, the APP tilted posteriorly to the vertical (-2.84°±11.37°), while in the supine position, where the APP is typically registered on theatre, it had a mean anterior inclination. Male participants tended to have an extended pelvis, while female pelves were more flexed in supine. This study further supports that APP is not vertical in standing, nor horizontal in supine, as it used to be assumed.

In agreement with the literature, a posterior APP tilt occurred in the transition from supine to the erect posture (-4.9°±9.59°), without recording any significant differences. However, supine APP tilt differed significantly from the lateral decubitus tilt and this may raise concerns on current protocols in navigation. There was a high negative pelvic tilt in the seated position (-29.76°±23.23°), significantly different from all other postures.

Finally, ISB-defined pelvic tilt represented the position of the pelvis in higher flexion angle values, as compared to the APP-registered pelvic tilt. APP angles were highly variable, as related to ISB angles, possibly due to anatomical variations. However, a positive linear relationship was determined (r=0.803).

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Contents

1. INTRODUCTION

This study stems from total hip arthroplasty (THA), which is one of the most common and successful orthopedic operations, with an increasing number of primary surgeries performed over the past seven years in Scotland and a decreasing mean age of the patients undergoing surgery (Perkins 2013). A major concern after THA is the prevention of orthopedic complications such as hip instability, hip impingement, increased wear and dislocation (Goel et al. 2014a). While these complications are limited to 1-1.5% in Scotland (Perkins et al, 2013), the incidence of a dislocation has a profoundly negative effect both personally to the patient and economically to healthcare, since a revision surgery might be required. Dislocation and related complications are multifactorial, linked to both patient-related and operative factors. The most widely recognized risk factor is the malalignment of the acetabular component which affects the weight bearing of articular surfaces and the biomechanics of the joint (Kennedy et al. 1998). The need for proper positioning of the artificial joint caused an increased interest in computer-assisted hip replacement surgery. Increasing the accuracy of cup placement is expected to decrease outliers and decrease the incidents of dislocation and poor function (Beckmann et al. 2009). Navigated hip surgery uses the Anterior Pelvic Plane as anatomical reference to plan and guide the surgeon to the considered "optimal" cup placement. However, there are issues related to navigated surgery, which affect the final functional result. Pelvic tilt affects the acetabular component orientation, and even if the cup is optimally positioned during surgery, with a change in pelvic tilt, the implanted cup may become functionally malpositioned (Dandachli et al. 2013). Moreover, intraoperative tilt may as well affect the final cup orientation (Grammatopoulos et al. 2014). Currently, researchers are trying to find ways of predicting pelvic tilt changes that are responsible for dislocation and impingement. Variables that affect sagittal balance are examined between postures and different groups of patients. There is an increased scientific interest on the quantification of postural pelvic tilt changes that could indicate optimal cup orientation for different patients, in order to bring a safer and more functional result. However, pelvic tilt between different postures of daily life remains under-researched, while to our knowledge there is only one radiographic study examining differences in pelvic tilt between operative and functional positions (Philippot et al. 2009).

In this study, we used an optico-passive motion capture system to examine pelvic tilt in normal subjects between different postures of daily life. Markers were attached on the lower limbs and pelvis as defined by the Vicon Plug in Gait model (PIG) and also on the lumbar spine. The variables that we analysed were pelvic tilt angle as defined by the ISB recommendations and the anterior pelvic plane inclination in the sagittal plane. The former angle is formed between the line joining the anterior superior iliac spines with the posterior superior iliac spines and a horizontal axis. It was defined positive or flexion angle when the posterior markers were superior to the anterior markers in the sagittal plane. The APP inclination angle is formed by the anterior pelvic plane and a frontal axis. The APP angle was defined positive (flexion angle), when the anterior iliac spines were located in front of the pubic symphysis in the sagittal plane. Both angles are currently used to define pelvic tilt, while the APP inclination angle is currently used in the description of pelvic tilt in hip arthroplasty patients and is usually measured in radiographs and CT-scans. In our study, the APP landmarks were located through palpation and pointed with a wand supporting two markers.

The postures that we examined were natural standing, sitting on a height-adjusted chair, lying supine and on the left side. Standing was selected as a functional position where most activities of daily living are performed (Miki et al. 2014) and where pelvic tilt participates in the lumbo-pelvic sagittal balance, defining the actual anteversion and inclination angles. The seated pelvic tilt is of interest as it is a functional position where dislocation is possible due to the increased posterior tilt that causes hip instability of the prosthetic hip. The supine position was analyzed because it is used as a position of registration of the APP since it resembles most the standing posture. Finally, the lateral decubitus position is the position where most surgeons prefer to operate.

We examined how pelvic tilt varies between different postures and if there are statistically significant differences between male and female participants. It was of interest to determine if pelvic tilt is significantly different between standing and supine. Moreover, we examined if a pelvic tilt change is expected to occur from the supine to the lateral decubitus position and from lateral decubitus to standing. If these changes are significant, they imply the need of adjustment of the operating protocol in computer assisted hip arthroplasty. Furthermore, we were interested in identifying the mean change in pelvic tilt between postures and the range of pelvic tilt in different postures. Finally, we examined the relationship between ISB and APP defined pelvic tilt angles, as both variables characterize quantitatively the same movement, but are defined based on different anatomical co-ordinate systems describing the same segment.

To the researchers' knowledge, there are no similar motion analysis studies which measure pelvic tilt between different postures, documenting APP angles. Moreover, the relationship between ISB and APP defined pelvic tilt remains unclear.

2. LITERATURE REVIEW

2.1 Pelvis and Hip Anatomy

The pelvis is a composite structure which consist of the pelvic bones and the sacrum and coccyx, joining the axial skeleton to the appendicular skeleton. The pelvic girdle consists of the left and right hip bones or pelvic bones (Martini et al. 2012). Pelvic bones are relatively large and heavy bones, “covered by thick and heavy muscles” (Floyd 2009), to bear the stresses of weight bearing and locomotion. Each comes from the fusion of three bones: an ilium, an ischium and a pubis. Posteriorly, the ilia articulate with the sacrum, forming the sacroiliac joints, while anteriorly, the pubic symphysis forms by the fibro-cartilaginous interconnection of the medial surfaces of the pubic bones. Sacroiliac joints are enhanced by strong ligaments so that only minor oscillating movement may occur. In a general definition of the pelvic girdle, movement between the three bones in the sacroiliac joints and pubic symphysis is assumed to be negligible (Cappozzo et al. 1995). On the lateral side of the pelvis, the concave acetabulum articulates with the femoral head to form the hip joints bilaterally (Martini et al. 2012).

2.1.1 Hip movement

The hip or acetabulofemoral joint combines mobility, comparable to that of shoulder joint, due to its multi-axial arrangement, as well as significant stability, as a result of its bony architecture, its dense ligamentous capsule and strong ligaments that reinforce the joint. While the exact range of hip motion remains controversial in the literature, it is generally acceptable that the hip moves in a range of 0 to 130˚ of flexion, 0 to 30˚ of extension, 0 to 35˚ of abduction, 0 to 30˚ of adduction, 0˚ to 45˚ of internal rotation and 0 to 50˚ of external rotation (Floyd 2009). The pelvic girdle can move within three planes of motion, as well. Nonetheless, the rotation of the pelvis happens as a result of motion at the lumbar spine or at the hips (unilaterally or bilaterally). Pelvic movement accompanies hip movement, increasing the phenomenal range of motion in three planes.

2.1.2 Pelvic movements

Many clinical descriptions of pelvic movement exist in the literature. Pelvic rotations may occur in all three planes or a combination of these. In kinesiology terms, anterior and posterior pelvic tilt occurs in the anteroposterior or sagittal plane. Right and left lateral rotation are described to occur in the frontal or coronal plane, while right (clockwise) and left (anti-clockwise) transverse rotation in the horizontal or transverse plane of motion. Anterior pelvic rotation describes the anterior movement of the upper pelvis (iliac crest) in the sagittal plane, while posterior tilt describes the opposite, posterior movement of the upper pelvis. Left lateral rotation is the superior movement of the left side of the pelvis relative to the right, whilst the right lateral rotation describes the opposite. Another description of these terms is pelvic obliquity. Finally, left transverse rotation is described as the motion of the right iliac crest anteriorly in relation to the left iliac crest, or else the rotation of the pelvis to the body's left, as observed in a horizontal plane (Floyd 2009). External and internal rotation are most commonly used terms for the described movement.

Pelvic rotation	**Lumbar Spine Motion**	**Right Hip Motion**	**Left Hip Motion**
Anterior rotation (Anterior tilt)	Extension	Flexion	
Posterior rotation (Posterior tilt)	Flexion	Extension	
Right lateral rotation (Negative obliquity)	Right lateral flexion	Adduction	Abduction
Left lateral rotation	Left lateral flexion	Abduction	Adduction

(Positive obliquity)			
Right transverse rotation (Right external rotation)	Left lateral rotation	Internal rotation	External rotation
Left transverse rotation (Left external rotation)	Right lateral rotation	External rotation	Internal rotation

Table 2.1: Motions accompanying pelvic rotation (Floyd 2009)

According to Baker (2001) conventional descriptions of the rotations do not stem from mathematically precise definitions and are not consistent in describing movement. Particularly, in anatomical texts, angles are defined according to global co-ordinate axes, ignoring the anatomical position corresponding to the anatomical set of axes. A clinical description that the author considered reasonable was the following:

- Rotation "is the angle by which one hip joint center is anterior to the other"
- Obliquity "is the angle by which one hip joint center is higher than the other"
- Tilt "is the angle of rotation about the medio-lateral axis of the pelvis"

He acknowledged the inconsistency in the definition of rotation, since as described above, rotation occurs is assumed to occur in the transverse plane of the pelvis rather than the horizontal plane. There appears a difficulty in defining the transverse plane, because in gait analysis it is usually defined as containing anterior and posterior superior iliac spines, assuming symmetry between sides. In the case of the horizontal plane, it being a non-anatomical but a random plane, it has an effect on the calculation of pelvic tilt, obliquity and rotation. Thus, 'true' horizontal plane is needed. Moreover, he proposed the following definitions:

- Rotation “is the angle of rotation of the pelvis about a vertical axis. It is the angle which the projection of the medio-lateral axis of the pelvis onto the horizontal plane makes with the laboratory medio-lateral axis.”
- Obliquity “is the angle of rotation of the medio-lateral axis of the pelvis out of the horizontal plane.”
- Tilt “is the angle of rotation about the medio-lateral axis of the pelvis.”

(Baker, 2001)

2.1.3 Hip and Acetabulum

The hip is a multiaxial ball-and-socket weight-bearing joint, composed of the head of the femur and the acetabulum. The acetabulum is formed by the fusion of part of the pubis, the ilium and the ischium, which are the three integrated bones which form the pelvis (Magee 2008).

The acetabulum opens laterally, anteriorly and caudally, but its orientation can be better described by the anteversion and inclination angles, which define its orientation in space. In order to establish a method of communication about acetabular orientation, either native or prosthetic, acetabular orientation is defined either as anatomical, radiographical or operative (by observation in the operating room) and various terms have been used to describe it (abduction, tilt, opening, flexion, cover, anteversion and inclination). The definitions describe the orientation of the acetabular axis, which are perpendicular to the socket plane and pass exactly through the center of the socket (Murray 1993).

Still, the anatomy of the native acetabulum seems to be highly variable. In a study of patients investigated for labral tears with MRI, the orientation of the transverse acetabular ligament showed that the operative anteversion varied significantly from 5.3°-36.1° (mean 23.0°-7.4°), and the inclination varied from 38.4°-50.3° (mean 45.6°-3.2°), suggesting a wide range of acceptable cup positions (Schmalzried 2009).

According to Murray (1993):

- Anteversion is achieved in the plane of flexion by rotating the longitudinal plane about the transverse axis. The anteversion angle is measured in the sagittal plane.
    - Operative anteversion (OA): the angle between the longitudinal axis of the patient and the acetabular axis as projected on to the sagittal plane
    - Radiographic anteversion (RA): the angle between the acetabular axis and the coronal plane. It can also be determined from lateral radiographs.
    - Anatomic inclination (AI): the angle between the transverse axis and the acetabular axis when this is projected on to the transverse plane
- The inclination is the angle between the acetabular axis and the longitudinal rod.
    - Operative inclination (01): angle between the acetabular axis and the sagittal plane (angle of abduction of the acetabular axis)
    - Radiographic inclination (RI): angle between the longitudinal axis and the acetabular axis when this is projected on to the coronal plane
    - Anatomical inclination (AI): the angle between the acetabular axis and the longitudinal axis

Radiographic orientation is the one determined in anteroposterior (AP) radiographs from the alignment of radio-opaque markers. Anatomic anteversion differs from radiographic anteversion accordingly to the abduction of the cup as it appears on AP radiographs. To simplify the definitions, one should think that operative anteversion is measured around a transverse axis, anatomical anteversion around a longitudinal axis and radiographic anteversion around an oblique axis. In the evaluation of dysplastic acetabula, information on the degree of cover of the femoral head superiorly and on the relative cover antero-superiorly and postero-superiorly, is essential, and can be measured through anatomical anteversion. However, in cases of THA and surgical procedures one should prefer operative anteversion and inclination to describe the cup component alignment (Murray, 1993).

However, the above definitions are related to the groung-based reference frame, while other reference frames (e.g. the pelvic frame reference) can be defined to describe the above angles independently of the anatomy of the individuals.

2.1.4 Reference Frames

In order to be able to describe position of a segment in a reproducible and generally acceptable way, one needs to define a coordinate axis system, typically based on three orthogonal axes. The body orientation defines a ground-based axis system, as visualized in the anatomic standing position. It is defined by the superior-inferior axis (SI), alternatively called cephalocaudal axis, the anteroposterior axis (AP) and mediolateral axis (ML), of which the sagittal, coronal or frontal and horizontal planes are formed. This reference system is more useful when analysing forces and loads exerted on the acetabulum relative to the direction of gravity.

However, the pelvis lies in a different frame, since it is tilted in the sagittal view (anteriorly or posteriorly), mainly due to variations in lordosis (McCollum & Gray 1990) and degree of hip extension while weight bearing. Moreover, pelvic tilt within the same individual changes throughout different activities and postures. As a result, the acetabulum, being part of the pelvis, changes orientation according to the pelvic girdle and in cases its orientation is measured in the global coordinate, there is no compensation for the movements of the pelvis and especially the pelvic tilt. That can lead to inaccuracies in describing the position of the acetabulum among patients and in the same individual among different postures, due to variations in the pelvic tilt (Yoon et al. 2008). As a result, it is preferable that descriptions of the acetabulum are referenced to the pelvic frame, so that measurements are independent of the position of the pelvis or the patient relative to the ground. Lazennec et al (2004) suggested the upper end plate of the first sacral vertebra (S1), while the most frequently used frame is based on the Anterior Pelvic Plane (APP), which is defined by the anterior superior iliac spines

(ASIS) and the anterosuperior surface of the pubic symphysis (pubic spines) (Lewinnek et al. 1978).

2.1.5 Anterior Pelvic Plane

The Anterior Pelvic Plane (APP) or the Lewinnek's plane is the plane defined by the left and right anterior superior iliac spines (ASIS) and the pubic symphysis. The APP is universally used as the reference plane for total hip arthroplasty since it helps identify the position where the acetabular cup needs to be implanted. Also, it is a reference plane of the pelvis and is used for retrospective evaluation of cup orientation (Pinoit et al 2007).

According to the Scoliosis Research Society, the APP used to be considered to be both horizontal in the supine position and vertical in the standing position. It was considered similar to the global reference system. However, great variations in the inclination of the anterior pelvic plane have been observed between individuals. Pinoit et al (2007) found it vertical in less than 50% of cases, with a posterior tilt of 5° in more than 38% of cases and 10° in 13% of cases. The author recognized that there are great intra- and inter-individual variations. Moreover, pelvic tilt was found to vary unpredictably between different postures (sitting, supine and standing) (DiGoia et al. 2006; Lazennec et al. 2011). According to Legaye, the APP is not always vertical but varies in inclination mostly because of spinal diseases which cause perturbations on the sagittal balance of the pelvis and the spine (Legaye 2009).

2.2 Total Hip Arthroplasty

Total hip arthroplasty (THA) is regarded as “Operation of Century”, as it has brought radical changes in the management of patients with advanced hip disorders. Pain and functional impairment such as loss of range of motion of the hip are symptoms that if not resolved through alternative treatment, require arthroplasty. The most common indications for THA are osteoarthritis of the hip and fractures of the femoral neck. Other conditions include dysplasia, avascular necrosis, impingement, Perthes disease, inflammatory arthritis etc. (Rajesh 2012).

THA is a very common and successful surgery, with an increasing number of operations performed over the past seven years, including 7609 registered primary hip arthroplasties in Scotland in 2013. At the same time, the mean age of patients receiving THA has decreased from 67.3 years to 66.4 years in the twelve years between 2001 and 2013. The main complications are dislocation, infection of the operated joint, deep vein thrombosis or pulmonary embolism (DVT/PE), acute myocardial infraction (AMI), acute renal failure, cerebrovascular accident (CVA) or stroke. The orthopedic complications, are limited to 1 - 1.5% in Scotland. The rate of revision surgery has increased from 23.3% to 27.6% between 2009 and 2013 (Perkins 2013), having a profoundly negative effect both personally to the patient and economically to healthcare. Other not registered complications that lead to reduced functionality, are impingement and instability, the latter f which is considered to be the greatest cause of revision in the US. Both instability and impingement can also lead to premature component wear and earlier need for replacement (Schmalzried 2009).

2.2.1 Dislocation

Hip dislocation remains one of the most frequent complications, with rates during the first 6 months after THA to range from 3.1% to 3.9% for primary THA and ranging from 2.6% to 14.4% for revision THA. Cases of dislocation that require revision surgery, seem to have poor functional outcome for the patient and reduce one's quality of life, especially if recurrent discolation occurs, as described by Kotwal et al. (2009) in a study with 99 dislocations, half of which were treated surgically, with a follow-up of 4.5 years. Functionally, the presence of joint instability due to mechanical loosening of the joint and the event of a dislocation are the commonest causes for revision surgery (Goel et al. 2014b). Dislocation is a multifactorial issue, linked to patient-related factors, such as preoperative range of motion (Krenzel et al. 2010), neuromuscular conditions, dementia, age, gender, and operative factors (Yarlagadda & Jones 2009). Operative factors include the selection of surgical approach, the management of soft tissues, the prosthesis selection and alignment. Posterior approach is known to make the joint more prone to dislocation. Moreover, the design of prosthesis, the size of the femoral head, and the acetabular component orientation combined with the degrees of anteversion of the femoral component play an important role in the risk of dislocation. Also these factors increase other risks associated with early revision surgery, such as premature component wear. Prosthesis design variables include acetabular component center of rotation (COR) and the femoral head–neck diameter ratio (Schmalzried 2009). A larger sized femoral head is considered safer, promoting stability and reducing the risk for dislocation (Goel et al. 2014b). However, the malposition of the acetabular component appears to be the most significant and common risk factor for dislocation (Sanz-Reig et al. 2015). When proper alignment is achieved, impingement and soft tissue factors may contribute to the event of instability or dislocation (Yarlagadda, 2009). There is the chance of dislocation due to subjective failure of soft tissue or local trauma after an excessive movement e.g. in an intense effort of rising from a chair, in patients who do not appear to have an increased risk of dislocation (Padgett & Warashina 2004).

In any case, every effort should be made in order to prevent episodes of dislocation as, once they occur, they are a burden for both the patient and the surgeon. The correct implant and surgical approach should be selected and the appropriate position needs to be achieved to minimize the risk of instability and dislocation. Nevertheless, dislocation still occurs after THA, underlining the need to address as many factors leading to dislocation as possible (Yarlagadda, 2009).

2.2.2 Acetabular prosthetic Alignment

Proper acetabular orientation is of paramount importance, since it influences the distribution of forces on the hip joint, the amount of bearing and nonbearing wear, the postoperative range of motion, potentially causing impingement or instability. More specifically, as it is reported by Schmalzried (2009), increased abduction of the cup has been related to excessive component wear, fractures of cross-linked polyethylene components, rim wear, stripe-wear of ceramic-on-ceramic bearings, as well as ion levels with metal-on-metal components. As a result, it vastly affects the short-term and long-term outcome of THA.

Inappropriate placement of the acetabular component is also associated with high dislocation rates and may also compromise the endurance of the artificial joint due to the effects mentioned above (Moskal & Capps 2011). Moreover, it may cause leg length discrepancy, pelvic osteolysis, acetabular component migration and poor hip biomechanics (Kennedy et al. 1998). These conditions are particularly important because they increase the cost for healthcare provider by requiring longer stays in hospital and more frequent revision surgeries. This also leads to decreased patient satisfaction and an increase in morbidity rates (DiGoia et al. 2006).

Generally, acetabular component position is described by its medio-lateral position, its abduction or lateral opening angle, and its degree of anteversion. It is highly desirable to bring the center of rotation of the femoral component medially, decreasing the lever arm of the body weight. A subsequent increase in the femoral offset can expand the lever arm for the abductor muscles, which control the pelvic-hip relationship during functional movements. This intervention can decrease the force that needs to be exerted by the abductors, resulting in a further decrease of joint reaction forces (Schmalzried, 2009).

As for the version and inclination angles, the combination of acetabular anteversion and anteversion of the femoral component characterizes the bearing of the joint. Abduction and inclination need to be studied together for optimal results (Schmalzried 2009). Lewinnek et al. (1978) was the first to introduce a desired range of angles, which he termed "safe zone", into which a surgeon should aim to reduce the risk of dislocation. He described a radiographic anteversion of 15±10° and an abduction of 40±10°. He stated that there is the risk of posterior dislocation when the cup is anteverted less than 5° and a risk of anterior dislocation if the cup was anteverted more than 25° (radiographic definition), which corresponds to 38° in operative definition according to Murray. At the time, it was recognized that this range was too narrowed and difficult to accomplish even from the best surgeons with the free-hand technique, while it is still questionable if the orientation of the cup that can be accomplished with navigated surgery would be functional for the patient (Parratte et al. 2009). The difficulty lies in defining a specific range of acetabular position which would be ideal for every patient, while the need to compensate for individual pelvic tilt is recognized by many authors (Kalteis et al. 2006; Dandachli et al. 2013).

Although there are authors who have not found results confirming the existence of a "safe zone"(Pierchon et al. 1994), many researchers have proposed a safe zone either by computer model simulations, or by relating the acetabular orientation to episodes of dislocation. However, most studies did not define the range according to the pelvic reference frame, but to the ground-based reference frame, which made comparisons between results difficult. In a review of Yoon et al (2007), the safe zones, proposed by the nine studies judged to be most reliable, were transferred to the pelvic reference frame as radiographic angles, assuming a pelvic tilt of -8° in standing and -4° in lying, based on the results of a study of Lembeck et al. (2005) on pelvic tilt of 30 subjects. This conversion made the results more consistent and comparable. The average recommended acetabular orientation expressed in radiographic angles and referenced to the pelvic frame was found to be 41° of inclination and 16° of anteversion. The anteversion angle seemed to depend significantly on the selection of reference frame (pelvic or ground-based) and the angle reference system (radiographic/anatomic/operative). Authors observed a 14° difference in the numerical values of differently-defined anteversion used to describe the same cup position (Yoon et al. 2008). A significant limitation and source of error in the study was the lack of information on the pelvic tilt of subjects in the various studies they reviewed. So, they assumed a pelvic tilt based on the study of Lembeck et al. (2005) and their previous unpublished study, due to the unavailability of other studies on pelvic tilt referencing the Anterior Pelvic Plane (APP).

2.2.3 Navigated Surgery

Computer-assisted surgery was introduced in total hip arthroplasty to improve cup positioning, reduce the variability in acetabular orientation which occurs using mechanical guides or the conventional method. Reducing the outliers may theoretically reduce the number of dislocations. Navigated surgery enables the surgeon to identify and perform optimal positioning of the acetabular component, through the creation of a virtual patient—specific model which comes from the registration of anatomical points during the procedure (Parratte, Aubaniac, & Argenson, 2008). Different computer-assisted hip navigation systems exist, which are generally classified in three types. First, there are navigation systems which are based on preoperative CT images, those that rely on intraoperative fluoroscopic images for planning and registration, and the imageless, intraoperative registration of bony landmarks. They all require the registration of the Anterior Pelvic Plane (APP) which, as previously described, is the plane created of three bony prominences of the pelvis, the anterior superior iliac spines (left and right) and the two promontories of the pubic symphysis. The orientation of the plane is used to evaluate the position of the pelvis and the aimed placement of the cup (Lin et al. 2011).

While the intrinsic error of navigated systems is very low, the registration of the Anterior Pelvic Plane in imageless assisted surgery depends on manual palpation of these anatomical landmarks, where there are overlying drapes and soft tissue, which might cause error in cup placement. (S Parratte et al 2008; Ybinger et al., 2007). In obese patients, the difference in orientation between bony APP and cutaneous APP will produce an error that will affect final cup position. An error of 5° during APP acquisition may cause an error of 5° in anteversion (Wolf et al. 2005). Moreover, according to the kinematic model of the authors, an error of 4 mm when identifying these landmarks would cause a 2◦error in inclination and7◦in anteversion in acetabular orientation, while the minimum thickness of the soft tissues above bone was found to be approximately 8 mm at the iliac spine and 13 mm above the pubic symphysis, which results in a mean underestimation of anteversion of 4.4°. Barbier et al (2014) in a level III prospective case control study, found that the APP lacks precision as a reference for positioning the cup, especially in relation to anteversion, because there are inter-individual variations and variations in orientation between positions. He also identified pelvic tilt variability and functional anteversion as additional causes of poor reliability, since position of pelvis is dynamic and not static during changes of positions and daily activities, with unpredictable variations.

A major concern is the ability to adjust the acetabular component position according to individual functional pelvic tilt. While published literature show a large interest in this field, there are issues to be clarified, especially on long-term pelvic orientation in patients undergoing THA (Beckmann et al., 2009; Lembeck, Mueller, Reize, & Wuelker, 2005; Parratte et al., 2008). A point of interest is that registration of the Anterior Pelvic Plane is usually performed once during the surgery, while intra-operative movement may occur from the time of registration to the moment of implantation of the cup (Barbier et al. 2014).

Navigated surgery has the disadvantage of increasing operating time, as acknowledged by many authors. Specifically, in the study of (Lin et al. 2011) the mean time increase was 21minutes, while other researchers calculated the extra operating time to be 8 minutes (Kalteis et al. 2006) and 12 minutes (Parratte & Argenson 2007). Despite the added operating time, navigation is a valuable tool that seems to reduce cup positioning variability as related to the manual method. It is estimated that with the upcoming designs and the increased awareness on factors related to cup malpositioning, navigation has the potential to introduce a new range of safe acetabular placement. Various factors such as individual pelvic tilt, anatomy, and assessment of patients' kinematics may lead to a more individualized approach, if incorporated in navigated surgery. (Lin et al. 2011)

2.2.4 Effect of pelvic tilt on Acetabular orientation

As mentioned above, the orientation of the pelvis influences that of the acetabulum. The orientation of the acetabulum may end up being markedly different from the surgeon's expectations, after THA, due to variations in pelvic tilt. That may negatively affect bearing surface performance especially of hard-on-hard materials and may also lead to impingement. Moreover, the interpretation of radiographs may become difficult due to pelvic tilt variations, causing subtle changes in the radiographic appearance of the acetabulum. That may be a deceiving factor in the diagnosis, the surgical planning and the evaluation of the result of a surgery (Dandachli et al. 2013).

A number of studies have investigated the influence of pelvic position on the spatial orientation of the acetabulum. Dandachli and colleagues measured acetabular anteversion, inclination and femoral head cover in a 3D-CT analysis, for pelvic tilt variations from -20° to 20° in relation to the anterior pelvic plane (APP), and found that there was a profound effect on anteversion, which reduced from 2.5-5° for every 5° of forward tilt. This effect was more intense at higher values of tilt. They also observed a lower effect on inclination which tended to be negligible in tilt greater than 15°. Stem et al. (2006) found similar results using axial CTs of a phantom pelvis and reported that acetabular version tended to be more affected after an anterior tilt of more than 6°.

Babisch et al. (2008) measured the effects of pelvic tilt on acetabular component orientation in a 3D-CT model and created a nomogram for use in navigated surgery, which would compensate for individual pelvic tilt, to optimize cup positioning. They reported a change in anteversion by 4° for every 5° of pelvic tilt and in inclination by 1.5° for every 5° of pelvic tilt. Generally, it is true that an anterior pelvic tilt (or flexion) induces a retroversion of the acetabulum and a posterior pelvic tilt an anteversion (Legaye 2009). Also, leg length discrepancy and pelvic obliquity are factors affecting pelvic inclination, while pelvic tilt and pelvic incidence are associated with changes in version (Tiberi et al. 2015).

Legaye et al (2009) studied the relationship between the acetabular orientation, the APP tilt and the sagittal balance of the spine and the pelvis, and proposed a compensation method to select proper acetabular anteversion and inclination angles to correspond to an acquired sagittal imbalance. A similar study was carried out by Tang and Chiu involving patients with ankylosing spondylitis. They suggested a reduction of the inclination and anteversion by 5° for each 10° of sagittal mal-rotation beyond 20°, but their assessment of mal-rotation was limited to the radiographic appearance of the obturator foramen. However, Legaye et al proposed that the results of their study could be incorporated into the CAOS (computer-assisted orthopedic surgery) system, so that individual sagittal imbalance would be accounted for, in order to avoid cup malpositioning.

Lembeck et al (2005) studied the range of pelvic reclination (the angle between the APP and the frontal plane) and its effect on the acetabular position. They stated that "Every movement of the anterior pelvic plane caused by tilting of the pelvis must result in a difference between intraoperatively prescribed implanting angles and postoperatively measured cup alignment". They measured that 1° pelvic inclination corresponds to 0.7° acetabular anteversion, and only due to the change of position from lying to standing by the end of the surgery, which corresponds to 4° pelvic inclination, the error in the placement would be 5.6° additional anteversion. This statement further supports the fact that a change in pelvic tilt on the operating table would finally bring a consequent variation in the prosthetic cup orientation, even with the APP being registered throughout the procedure.

What makes matters worse is the possibility of change in pelvic tilt between different positions and in the long-term postoperative period. While the surgeon usually refers to the orientation of the pelvis in the supine position and at the time of the surgery, the pelvis may have different orientation in the standing position and in the long-term post-operative period. The supine position is preferred in registration as being representative of standing posture where most daily activities happen (Taki et al. 2012). However, a positional and a temporal change need to be expected first due to change from supine to standing. Many authors have recognized the posterior tilt of the pelvis as a reason of edge loading and impingement of the prosthesis, since it results in retroversion of the acetabulum. Preoperatively, the change in pelvic tilt from supine to standing usually happens in the posterior direction and this condition remains short-term after surgery (Babisch et al. 2008). A large posterior tilt of more than 10° has been reported in approximately 10% of patients, due to positional and temporal shift (Taki et al. 2012). This posterior change has been associated with increased age and degenerative changes of the lumbar spine (Kyo et al. 2013). A maximum change in pelvic tilt from the preoperative supine to the standing posture of 23° has been reported in a patient whose cup inclination was within 50°, when the original cup inclination aimed at 40°, even if maximum posterior tilt was noticed. Miki et al suggested that the aim of the surgeon should be 40 degrees of inclination (Miki et al. 2014).

While temporal and positional changes in pelvic tilt are not completely elucidated in the literature, the mean (±2SD) angle of preoperative positional change pelvic tilt to the posterior direction was reported to be 14-19°, while the mean (±2SD) postoperative posterior temporal change in the standing position has been found to be 13.6-19° (Parratte et al. 2009; Miki et al. 2014; Taki et al. 2012; Babisch et al. 2008). As for the temporal posterior change, some authors have identified a posterior change in pelvic tilt of within 10° in 84% to 89% of all patients, in the postoperative period of 1 to 4 years after THA, with the 95% upper limit reaching 19° of change (Taki et al. 2012; Parratte et al. 2009). It has also been recognized that changes seem to plateau after the first year of THA.

Research aiming to identify patient groups expected to show significant postoperative posterior change in tilt, shows that it occurs in patients with increasing kyphosis. During weight bearing, the pelvis tends to tilt posteriorly to compensate for the kyphosis (Roussouly & Pinheiro-Franco 2011), which is associated with increased age, osteoporosis, compression fractures of the vertebrae, disk regeneration and weakness of the back muscles. Additional factors leading to posterior pelvic tilt are spondylolisthesis and disk-space narrowing (Kyo et al. 2013; Tamura et al. 2014). The importance of taking into account spinal conditions during the planning of THA is highly recognized. (Miki et al. 2014)

Finally, pelvic tilt varies significantly between individuals, does not remain stable among positions and time. The incorporation of individual pelvic tilt in the determination of the acetabular parameters in THA can improve the functional outcome of the surgery. Finally, a better understanding of the effect of pelvic tilt may bring better results in both the planning and effectiveness of acetabular reorientation procedures including THA (Dandachli et al, 2013).

2.2.5 Intra-Operative Pelvic Orientation

During total hip replacement, information on intraoperative pelvic orientation and especially pelvic tilt enables the surgeon to position the acetabular and femoral components in the appropriate orientation to achieve optimal biomechanical function of the hip (Asayama et al. 2004).

The majority of hip arthroplasties are performed in the lateral decubitus position with the patient’s pelvis stabilized as firmly as possible. However, rolling motions forwards and backwards can easily occur, either during the fixation of the pelvis on the operating table, or during the surgery, because of leg movement or the unavoidable surgical manipulations of the limb (Asayama et al, 2004). For the cup positioning to be accurate, the surgeon needs to know the exact position of the pelvis at set-up, as well as during the procedure.

Conventional (non-navigated) surgery does not provide information on pre- or intra-operative pelvic tilt and the estimation of pelvic orientation depends solely on the surgeon's subjective judgement. In either cases, at set-up, the surgeon aims to position and stabilize the pelvis in a neutral orientation, with the pelvic coordinate system parallel to the reference system of the table. The surgeon needs to identify anatomical landmarks as reference to position the pelvis. However, in the absence of a navigation system, it cannot be reliably and repeatedly positioned in neutral, nor should it be expected to remain stable until the impaction of the prosthesis (Grammatopoulos et al. 2014). While there is little information available about intraoperative pelvic orientation, navigated surgery is expected to bring light in this field.

Grammatopoulos et al. (2014) studied intraoperative set-up and pelvic movement and found a wide variability in the set-up of the pelvis by the same surgeon and between surgeons (mean/SD; tilt: 8°/16°, obliquity: -4°/6°, rotation: -8°/7°), as well as variability in pelvic movement (mean/SD: 9°/6°). These factors seem to contribute to the observed variability of acetabular positioning. Pelvic tilt varies significantly in the set-up position, deviating from neutral in most cases, while surgeons seemed capable of taking individual tilt into account. In the current study, most hemi-pelvises were set initially towards external rotation. During the procedure, internal rotation mainly occurred. Another significant finding was that pelvic movement varies according to pelvic support, surgical approach and procedure type. Specifically, three-point stabilization from double-anterior and single-posterior support appears preferable, whilst posterior approach may generate more pelvic movement, due to the stronger joint retraction and leg-twisting maneuver needed.

Asayama et al. (2004) also studied intraoperative pelvic motion. The researchers developed a device, described as 3-direction indicator, which identifies changes in 3d orientation when implanted on the anterior superior iliac spine (ASIS) during surgery. Similarly, they found significant variability in pelvic movement and internal rotation of the operated side as the main movement during the operation, which may lead to decreased cup anteversion.

2.2.6 Pelvic Orientation in different postures

Pelvic orientation is highly variable and represents individual posture and anatomy (Stephens et al. 2015). The adoption of a standing posture happens through complex modifications of static balance of the spine and pelvis, especially in the sagittal plane. Standing posture varies according to morphotype, age and pathology (Philippot et al. 2009).

While pelvic orientation has been studied as part of the spine through the sacrum, its position in the sagittal plane has been widely documented. However, most of the authors used variables such as sacral slope, which showed significant correlation with spinal parameters, without referring to APP orientation. Strong relationships exist between lumbar lordosis, sacral slope and pelvic incidence. As a result these parameters are considered as the most relevant to describe functional sagittal orientation of the pelvis (Rousseau et al. 2009).

Legaye (2009) showed that pelvic version added to sacral slope, equal to pelvic incidence, which is an anatomical parameter, constant in a given patient. These variables may be used to describe the orientation of the pelvis in the sagittal plane. However Philippot et al. (2009) were the first to analyze these positional pelvic parameters in the standing, seated (in 90° knee flexion) and lying positions, using the EOS system in a cohort of elder people. The variables that they measured, pelvic version and incidence, are radiographically defined angles that can be analyzed only in the presence of radiographs or other imaging of bony anatomy. He found that pelvic version significantly increased by an average of 22°, when the subject moved to a standing or supine position from a seated position, while the sacral slope significantly decreased by an average of 22°. The authors documented that in the supine position they found a hip flexion difference of 20° related to standing. Additionally, the angle of the anterior pelvic plane to the vertical axis of the body (LVA as defined by the authors) was not statistically different between the supine and standing position, but showed a statistical difference in the seated position. During standing and sitting, APP plane was found to be 4° behind the vertical plane or behind the horizontal plane in the supine position. Finally, the authors have identified a pelvic parameter, the pelvic-Lewinnek angle (PLA) that remains constant for a certain individual despite positional shift of the pelvis that could serve as a reference parameter if integrated in navigation software. It is defined as the angle between the sagittal representation of the APP and the line passing through the center of sacral plateau and the center of femoral heads (Philippot et al. 2009).

In the sitting posture, the interdependency of lumbar spine and pelvis is highlighted in the study by Stephens et al (2015), where he explains that pelvis posterior tilt in sitting requires more hip flexion and lumbar flexion to accommodate the posture. When hip flexion is insufficient, that will force the pelvis into posterior tilt to allow sitting position and consequently, lumbar spine will flex, flattening the natural lordosis. Both pelvic rotations in the sagittal plane are known to bring the hip closer to each range of flexion and extension. There is a linear relationship between lumbar and hip movement in the sagittal plane in the seated posture, with the resultant sagittal pelvic tilt being determined from the available lumbar and hip range of motion. As a result, when hip flexion is limited, the pelvis tilts posteriorly. However, a high variability exists in how pelvic anterior and posterior pelvic tilt occurs in different individuals (Stephens et al. 2015). This lead the author conclude that according to the movement pattern of each THA patient, anteversion should be individualized. In individuals who stand and sit with an extended pelvis should be treated with greater acetabular anteversion (25°), while in patients with anterior tilt and hip flexion, anteversion should be reduced to reduce the risk of posterior impingement. According to DiGoia et al, measuring changes in pelvic tilt between sitting and standing preoperatively, can give important information to improve the accuracy of acetabular positioning (DiGoia et al. 2006).

In another study, Kanawade et al. (2014) in a radiographic study documented sitting and standing pelvic tilt angle as defined by the vertical axis and the orientation of the projected anterior pelvic plane in the sagittal plane. Stiffness level was defined according to the amount of change in pelvic/sacral tilt between seated and standing radiographs. They found that pelves with normal stiffness tilted posteriorly 20 to 35° from sitting to standing. Stiff pelves had a mean of 4° less tilt than pelves with normal stiffness and a mean of 13° less tilt than hypermobile pelves, in the seated position, in the sixth postoperative week. The difference between the predicted and actual acetabular inclination due to postural tilt was quantified on a phantom model in the seated position according to the pelvic tilt. The values of the new inclination resulted in a more vertical cup, putting at risk of dislocation and increased component wear patients with supine coronal inclination of ≥50° and anteversion of ≥25° and the patients with hypermobile pelvis. The author concluded that pelvic orientation during postural change is the main parameter to affect surgical cup placement.

While these studies elucidate on the important effect of postural change in pelvic tilt and acetabular cup placement, to our knowledge, previous research has involved radiographic measurements and changes among different positions of daily activities have not been documented in motion analysis studies.

3. METHODOLOGY

3.1 Training and method testing:

Before proceeding to this study which is the dissertation MSc thesis of the researcher, training for the use of the Vicon system and testing of various methodologies were carried out. During this process, the researcher had the chance to familiarize with the system by learning how to adjust and calibrate the cameras, try different origin set ups, capture data, run processing pipelines and test various aspects of our methodology: for the purpose of the study

1. Different marker configurations were tested. We started implementing PIG Full Body Model. Through analysis of data we decided to limit our outputs to the lower limb model outputs. A marker configuration for the lumbar spine was added in order to establish the coordinate system of the segment and measure 3D angles. From the beginning of the project, the aim was to establish sagittal relationships of the pelvis, lumbar spine and lower limb. Later, we concluding on focusing on the pelvic segment.
2. Different camera set-ups were tested in the laboratory as pilot testing, in order to be able to measure pelvic kinematics in the supine position, where there was occlusion of markers. Upon trials, we decided to work in the full workspace of the lab with a configuration of twelve cameras for reasons of simplicity and practicality and for higher accuracy.
3. Different postures: there was a need for standardization in our methods. Therefore, we tried to be specific in the instructed postures that the individual had to acquire during the study, whilst keeping the concept simple and practical. Different bed and table configurations were tested, for the lateral position to ensure all markers are visible. We standardized the position of the furniture, by marking the lab’s floor, so that orientation in space does not change between subjects.

3.2 Departmental ethics approval

Departmental ethical approval was granted before the involvement of any participant in the study. For this purpose, a risk assessment came through where all possible risks during the experiment were documented and evaluated, according to the University's Safety Regulations. A Participant's Information Sheet (PIS) as well as an Ethics Application form were completed by the researcher, describing the purpose of the study, the methods involved, the exclusion criteria, sample size, the method of recruiting participants, the requirements of the study and relative sections. An advertising email which was sent to students and staff of the Department, was also approved by the Departmental Ethics Committee. (Forms are included in the appendix.)

3.3 Participants

Thirteen healthy volunteers from the University were recruited as participants in the study. Participants were excluded if they had a Body Mass Index (BMI) higher than 30kg/m^2, so that error on the position of external markers on the subjects' body due to skin movement would be limited to an acceptable extent. Other exclusion factors were acute or chronic pain due to musculoskeletal conditions, pregnancy, or having recently given birth, because these factors appear to influence posture (van Wingerden et al. 2008) (Franklin & Conner-Kerr 1998). Moreover, participants were excluded if they suffer postural instability, any neurological, visual or hearing impairments, which would affect balance or inhibit the individual's adherence to the experimental protocol, due to the inability to follow instructions or remain in a static position unassisted.

3.4 Methods

The study was performed using an optical-passive motion capture system for three-dimensional motion analysis (Vicon Motion Systems) in the Biomechanics laboratory of Strathclyde University. The system consisted of twelve infrared light-emitting cameras (Oxford Metrics, Oxford, England), which captured the movement of 19 reflective markers mounted on anatomical landmarks of the lower limbs, pelvis and lumbar spine of the subjects, with a sampling rate 100Hz.

The 3D-orientation of the pelvis and right femur was acquired and pelvic angles (tilt, obliquity and rotation) were evaluated in five static postures of daily living in twelve individuals. The analyzed poses were the spontaneous standing, sitting and supine decubitus posture of each participant, as well as the instructed lateral decubitus position in relative extension of the hips and in approximately 30 degree hip flexion, which was acquired with the guidance of a simple goniometer. Additionally, the orientation of the Anterior Pelvic Plane (APP) was acquired in each position.

The PIG lower body model, which is the commercial model of Vicon Motion systems for the Conventional Gait Model (Levine et al. 2012), was used for the analysis of the pelvis and lower limb marker trajectories to produce kinematic data of the segments. The processing was performed using the Vicon Plug in Gait Model (PIG). Cardan angles were employed to describe the orientation of the pelvis to the global (laboratory) frame of reference. The orientation of lower limb segments was defined relative to the pelvic reference frame.

Additionally, the orientation of the APP in the global frame of reference was measured. The position of the landmarks was found through the registration with a wand. The researcher would first palpate the bony prominences below the soft tissue and then point consecutively the right, left anterior superior iliac spines and the anterior rim of the pubic symphysis. The wand marker trajectories were analyzed in Matlab to produce the position of the points (see script in the Appendix) and the defined points were processed to find the orientation of the plane, using ProCalc. The change in pelvic sagittal orientation from each position to another, referred to the APP, was compared to the change in pelvic sagittal orientation, as defined by the PIG model.

3.4.1 Marker set

The marker set used was the one described by Vicon Plug-in Gait Marker Placement Manual with the addition of three markers on the sacro-lumbar spine. The markers were attached by the researcher according to the manual script. Participants were standing in an upright posture, leaning equally on both limbs, with their feet wide open in alignment to the pelvis and pointing forwards. Markers were attached on the following anatomical landmarks on both left and right side of the body *(see figure 3.1)*:

- Anterior Superior Iliac spines (LASI and RASI)
- Posterior Superior Iliac spines (LPSI and RPSI)
- Lateral thigh (LTHI and RTHI)
- Lateral epicondyle of the knee (LKNE and RKNE)
- Lateral tibia/shank (LTIB and RTIB)
- Lateral malleoli (LANK and RANK)
- Dorsal distal aspect of the second metatarsal head (LTOE and RTOE)
- Posterior aspect of the calcaneus (LHEE and RHEE)

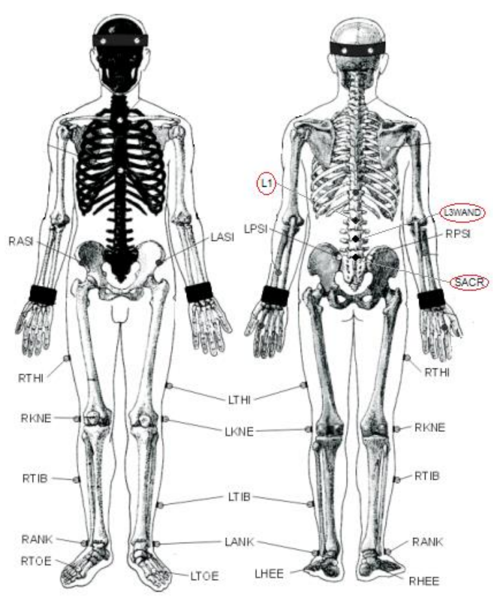


Fig 3.1 Plug-in Gait marker placement, with the additional marker configuration of our study in the lumbar spine. Source: PIG Marker Placement http://www.idmil.org/mocap/Plug-in-Gait+Marker+Placement.pdf

Care was taken to place the lateral thigh on the axis defined by the greater trochanter and the lateral knee marker and the lateral tibia markers on the axis defined by the lateral knee marker and the lateral malleolus marker. Any antero-posterior deviation would create error in the kinematic data and the hip joint center definition through Newington-Gage model. Additionally, for the pelvis markers, the exact points were located through palpation and the markers were attached directly. In men, due to the abdominals prominence, both LASI and RASI were placed equally lateral, but in the same level. The inter-ASIS distance was measured and registered as a model parameter in all participants.

Additionally, for the lumbar segment:

- Spinous process of the first lumbar vertebrae (L1)
- Sacrum (SACR)
- Wand marker on the spinous process of the third lumbar vertebrae (L3WAND)

The specific marker set was chosen for the collection of kinematic data of the pelvis and lumbar spine. It would facilitate the measurement of the pelvic orientation using the PIG model, and lumbar orientation, using ProCalc between individuals among four different static postures of daily life. The selection of the marker set will be justified in later section.

3.4.2 Registration of pelvic markers

For the pelvic coordinate system to be documented, the position of at least three markers is needed to define the segment. In other words, at least three markers need to be visible to have kinematic output variables of the pelvis. The difficulty in this particular study was the occlusion of the pelvic posterior marker in the supine position. The researcher identified one of the following methods to address this limitation:

- the development of a bespoke biomechanical model for the specific position:

- By creating a cluster pelvic marker and a Vicon BodyBuilder or a MatLab model to identify intersegmental orientations, which would produce variability in the definition and measurement of pelvic angles. This would make comparison between postures difficult. Additionally, suggested cluster models for the pelvis usually involve the posterior side (Kisho Fukuchi et al. 2010; Vogt et al. 2003; Bohrani et al. 2013).
- By integrating technical markers at the iliac crests on the same level as the PSIS which also requires Vicon BodyBuilder programming. However, Fukuchi et al (2010) stated that a common problem with these landmarks is the amount of fat and skin tissue that might be present, which may reduce the method's reliability. McClelland et al. (2010) studied the use of alternative markers, in case of occlusion of the ASIS markers in gait analysis, where limb movement may obstruct raw data acquisition of the ASIS trajectories. The ASIS occlusion is more challenging than the PSIS since it affects both pelvic kinematics and lower limb kinematics and kinetics, due to error in hip joint center determination. The authors compared various methods of compensating for a marker occlusion and referred on the reliability of those. To our knowledge, there is no reference on how to compensate for PSIS occlusion in optical-passive motion capture systems that could serve the purpose of this study.

- With the placement of a wand-mounted marker on the sacrum, whilst positioning some of the lab's infra-red cameras on a lower level:
  The researcher had to make sure that the marker is not hidden by the bed (by using two beds with a space between or a bed with a hole) and that the wand would not be initially misplaced or displaced later when the person lied supine. The change of wand orientation would produce error in the measurement of kinematics and especially of tilt, since according to the model, tilt is defined by the angle of superior/inferior position of the anterior markers (ASISs) relative to

the posterior markers (PSISs) as described in a following session. Thus the orientation of the wand is critical, while according to the PIG manual, the length of the wand is not. We tried to use the conventional marker model with the person lying on two tables with the opening corresponding to the PSIS, while using an individualized set of eight Bonita cameras, appropriately calibrated to register the PSIS in the supine position, but it was not practical enough to take all measurements.

- With a wand supporting to collinear markers, in the same set up used above, without the need to position any cameras lower. Artificial markers were created for the resultant coordinates of the RPSI and LPSI in MatLab and imported back in Vicon Nexus and Vicon ProCalc to acquire kinematic data.

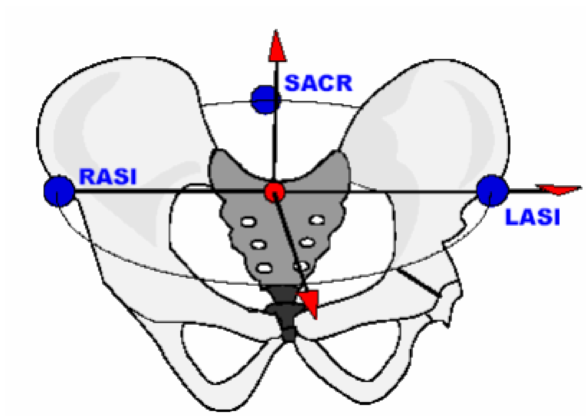


Fig 3.2 Required Pelvic Markers. Source: Plug in Gait manual.
http://www.irc-web.co.jp/vicon_web/news_bn/PIGManualver1.pdf

3.4.3 Experimental Protocol

Subjects participated in the study with bare feet and clothes that would allow marker placement directly on the skin. First, anthropometric data of the subjects was measured (height, weight, inter-ASIS distance, leg length, knee and ankle width of both limbs), and inserted in the model as required parameters. Markers were attached according to the model's instructions. In the case of the lumbar markers, care was taken to identify the specific vertebral level's spinous process and to strictly position the wand marker in the anterior-posterior plane of the body, as required for reliable results. Markers were placed by one examiner, who was a trained physiotherapist. The position of the markers is expected to correspond with spine kinematics, since the fascia over the spinous processes is firmly fixed to bone. Thus, skin movement reflects bone movement closely (Mörl & Blickhan 2006; Vogt et al. 2003; Schache et al. 2001).

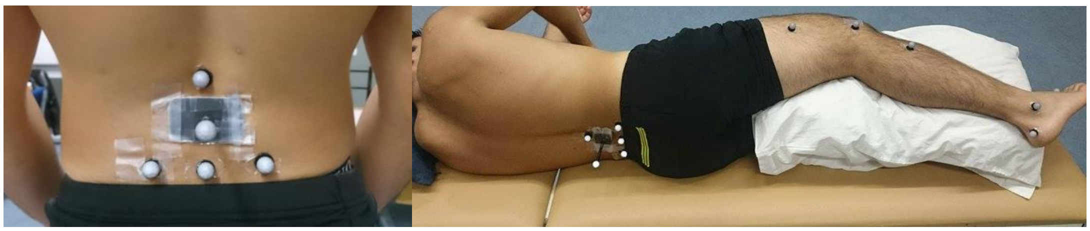


Fig.3.3 Lumbar marker set

Following marker placement, the participants were instructed to walk in their casual pace around the laboratory for 1-2 minutes, to feel comfortable with the markers. Then, a static capture was taken in the standing anatomic position and then the participants were encouraged to acquire their normal posture. For the purpose of this study, standing, sitting, lying supine, and the lateral decubitus position were selected.

Standing and sitting postures in a height-adjusted chair (so that femurs were nearly horizontal) were performed consecutively three times each. Data was captured for about 300 frames in each posture, with a frame rate of 100Hz. Average angular kinematics of the three trials in each position were used for statistical analysis.

In the final trial of each position, the person was instructed to maintain the position, while the researcher would palpate and point with a wand supporting two collinear markers, the anterior superior iliac spines (LASI and RASI) and the anterior rim of the pubic symphysis. In this way, the position of the wand markers would be registered and the exact coordinates of the landmarks calculated, which would be used to identify the orientation of the APP in each position. According to our experimental protocol, if any movement was noticed to occur during the registration of these points, the captured data in the specific trial would be excluded from the analysis and the registration of the APP in the specific position would be repeated. The alteration of the static posture may be a spontaneous reaction of the individual, or may result from palpation and pressure applied by the researcher when trying to identify the bony landmarks. In both cases, such movement would produce significant error, since during the registration of a point the pelvis needs to remain static. However, this method of registration is advantageous over the attachment of a marker, because it allows the researcher to push soft tissue aside and point on the bony prominences in each case, minimizing the error in the inclination of the plane due to the variable soft tissue thickness above the landmarks, which was underlined by many authors (Lembeck et al. 2005; Lin et al. 2011; S Parratte et al. 2008; Richolt et al. 2005; Ybinger et al. 2007; Wolf et al. 2005).

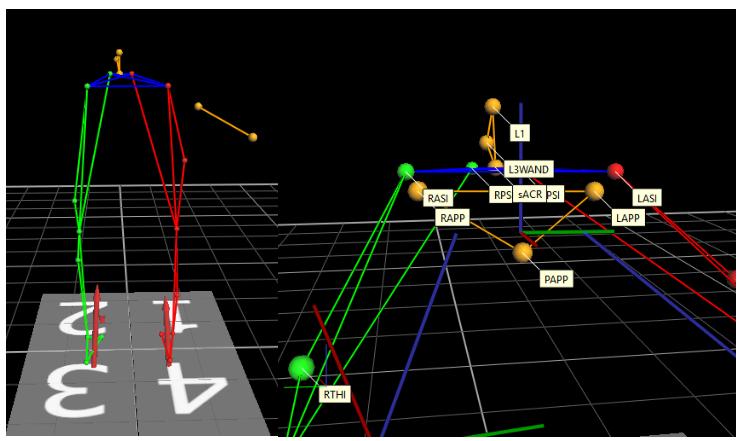


Fig.3.4 Left: Pointing the LASI with the wand in the standing posture. Right: Complete marker set with the APP triangle from wand acquisition landmarks.

Following the standing and sitting postures, the participants lay on their left side. The researcher tried to position the pelves in a vertical position (without external/internal rotation of the pelvis through visual inspection). There was no support for the pelvis, or limbs, with the exception of pillows between the lower limbs to maintain the hips in a neutral position of abd-adduction and internal-external rotation, as possible. The upper limbs of the participants were positioned in a specific way, as shown in the picture below, to provide some support for the upper torso. In the first lateral position, the participants had their hips positioned in relative extension. The posture was adjusted to be comfortable and easily maintained by the individual, since the comfortable range of motion of the hip differs among individuals. In the second lateral decubitus position, the researcher tried to change only the flexion angle of both hips to 30 degrees of flexion, with the knees slightly bent, with the use of a simple goniometer to enable positioning of all participants in similar positions. The angular position of the hips was evaluated after the experiment. Finally in the supine position, the participant was instructed to lie on one's back, with one's legs straight and a single pillow below the head. Two beds were positioned in a 8cm distance so that the person would lie with their PSIS in the gap between the beds, to allow for palpation of the PSIS with the wand. In the supine position, the PSIS are not a pressure point, so lying supine without support for these points is not expected to affect the results. This would enable the registration of the posterior anatomical landmarks of the pelvis, which are required for the execution of the PIG model in this static posture and whose markers would otherwise be hidden from the infrared-emitting cameras. In this case, the researcher used the wand to point and register the right and left PSIS, after having registered the anterior pelvic plane landmarks. In all cases the researcher used the same sequence to register the landmarks.

Fig.3.5 Lateral decubitus in relative hip extension.

3.5 Calculations

3.5.1 Positions and Laboratory Frame of reference

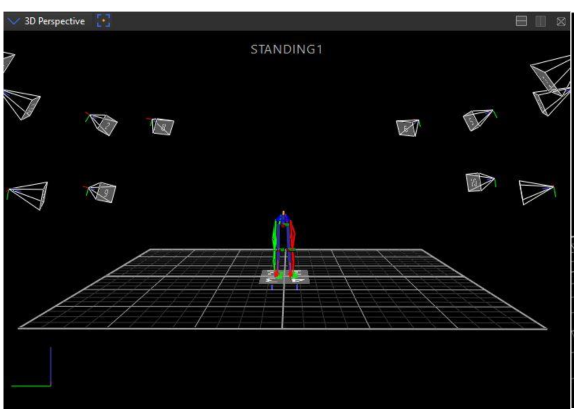
This study follows the description of Plug the transverse axes pass from one side of the body to the other (medial-lateral), sagittal axes pass from the front to the back of the body, and frontal axes pass in a direction from the centre of the body through the top of the head.

The laboratory coordinate system as set in this study, dictates that the z-axis is the vertical axis with an upward direction (caudal to cranial), the y-axis is in the medial-lateral direction of the standing individual, pointing from left to right, and the x-axis is the anterior-posterior axis with a posterior direction. In other words, z-axis represents the "frontal" global axis, y-axis represents the "transverse" or medio-lateral global axis and the x-axis represents the "sagittal" or antero-posterior global axis. This is true when the person is standing or sitting, facing towards the negative direction of the x-axis. However, in case the person lies supine or on the side, the given laboratory axes do not correspond to the above description and do not relate to the same anatomical set of axes. (Table 3.1)

Lab axes:	Standing/Seated	Supine	Lateral
x-axis	Sagittal Anterior → posterior	Frontal Caudal → cranial	Frontal Caudal → cranial
y-axis	Transverse (M-L) Left → Right	Transverse (M-L) Left → Right	Sagittal Anterior → posterior
z-axis	Frontal Caudal → cranial	Sagittal Posterior → Anterior	Transverse (M-L) Left → Right

Table 3.1: Lab axes relative to body axes in different static postures

In the supine position, the subject lies parallel to the x-axis with the head on the positive side and the feet in the negative x-direction. Consequently, the x-axis corresponds to the frontal axis of the body with a cranial positive direction, the y-axis corresponds to the transverse axis with a left to right positive direction, and the z-axis represents the sagittal direction with a positive anterior direction in this case (the supine sagittal z-axis is opposite to the standing sagittal x-axis based on the right hand convention). (Table 3.1)



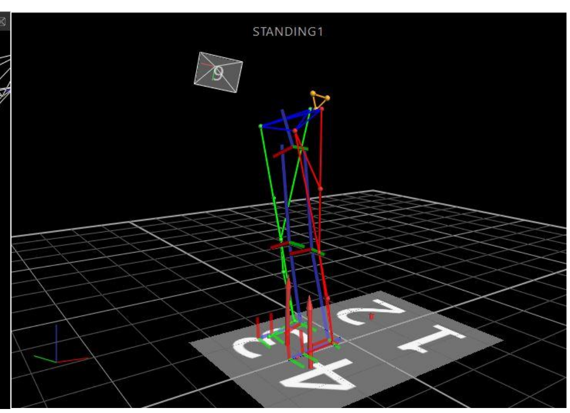


Fig.3.6 Left: 3D perspective of the workspace with a subject in a standing posture. Right: The same subject from another perspective. Notice the lab coordinate system on the left corner. (x:red, y:green, z:blue)

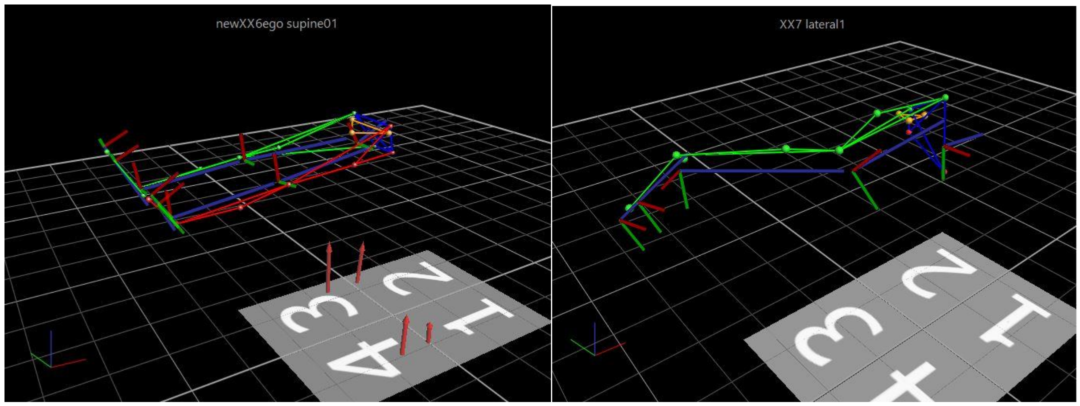


Fig.3.7 Left: Supine position. Right: Lateral position. Notice the lab coordinate system on bottom left corner in each image (x: red, y: green, z: blue)

In the lateral position, the person lies on one's left side, facing the negative y-direction of the lab, with one's longitudinal body axis strictly parallel to the x-axis. The z lab-axis now corresponds to the transverse axis with a left to right positive direction; the y lab axis would represent the sagittal axis, with a posterior positive direction and the x lab axis will be in the transverse direction with a positive cranial direction. (Table 2.1) In any case, it should be made clear that the laboratory set of axes cannot be considered to be concomitant with the body set of axes (anatomical).

Due to these axes changes from one posture to another, gait analysis models which define the relationship between lab axes and body axes according to the line of progression and always define the vertical axis as the caudal-cranial or frontal axis, are not predicted to give correct kinematic output in a single session for all three postures. During the calibration of the system, setting the origin according to the needs of the research may help overcome this problem.

3.5.2 Local coordinate systems

The pelvis segment coordinate system is defined by the PIG model, using the trajectories of the waist markers (left and right ASIS and PSIS). The midpoint of the two ASIS is defined as the origin of the segment. A principal vector from the right to the left ASIS marker is defined as the Y axis. A secondary axis is taken in the direction from the midpoint of the posterior markers (LPSI and RPSI) to the right ASIS marker. The Z pelvic axis is the dot product of these vectors, and is perpendicular to the plane these two vectors define. It is denoted an upwards positive direction, while the X-axis is positive forwards. Thus, the ASIS markers are important to define the origin of the pelvic segment and its coronal orientation, while the posterior markers are used for the measurement of pelvic sagittal tilt. The transverse distance between the anterior and posterior pelvic markers is of no particular importance. This definition of pelvic coordinate system corresponds to the ISB recommended Anatomical coordinate system (Wu & Cavanagh 1995).

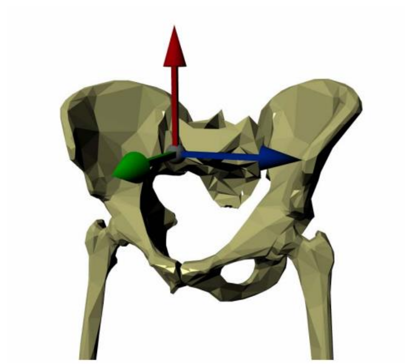


Fig. 3.8 Pelvic Coordinate System. Source: Plug in Gait Manual
http://www.irc-web.co.jp/vicon_web/news_bn/PIGManualver1.pdf

3.5.3 Angle Definitions

The model (PIG) uses Cardan angles to represent absolute rotation of the pelvis and foot segments, and relative rotations for other body segments (hip, knee and ankle joints). Absolute rotations are calculated when the angles of rotation are described in reference to the global coordinate system. These angles can be described as an ordered sequence of rotations as suggested individually by Davis et al. (1991) and Kadaba et al. (1990), or as a rotation axis fixed in either segments and a “floating” rotation axis mutually perpendicular to the other two, creating a set of non-orthogonal axes or a Joint Coordinate System (JCS), with two embedded axis and a floating axis, as it has been proposed by Grood & Suntay (1983) and Cole et al. (1993). Both descriptions are mathematically equivalent (Vicon Plug-in Gait Manual).

The output angles are calculated from the YXZ cardan angles. For the absolute rotations of the pelvis, the laboratory axes are fixed. When the pelvis moves, rotations happen about its axes. The ordered rotations assume that the first rotation is flexion (tilt), about the common flexion axis (y-axis). After this rotation occurred, the other two axes are no longer those aligned to the segment. The next rotation occurs about the new abduction axis of the moving element or x’-axis (obliquity), producing a new set of axes that are aligned to the moving segment. The final rotation that is assumed to occur is rotation, about the new rotation axis (z’’-axis). This process is required to define the 3D orientation of a segment in space. A basic limitation and source of error in the transverse and frontal plane kinematics is that the angles result from a calculation process which is sequence dependent (Kadaba et al. 1990). For a given rotation, the results may vary according to the sequence used, since multiplication of matrices is involved (Schache et al. 2001). While most motion data analysis software packages (e.g. Vicon Clinical Manager: Oxford Metrics, UK, Coda: Charnwood Dynamics, UK, Elite: BTS, Italy, Motus 2000: Peak Performance Technologies, USA) use the Tilt-Obliquity-Rotation sequence (TOR or YXZ) as it is considered logical for hip and knee joints (Baker 2001) and as proposed by the International Society of Biomechanics (Wu & Cavanagh 1995), it is controversial if derived angles from the given sequence correspond to conventionally defined anatomical terms (Baker 2001). The author showed that if TOR sequence was used in a calibrated pelvic model fixed to have both hips in the same level (clinically lacking obliquity), with varying tilt and rotation to common gait analysis values, the obliquity would be found to reach 10° in extreme values. He concluded that the sequence

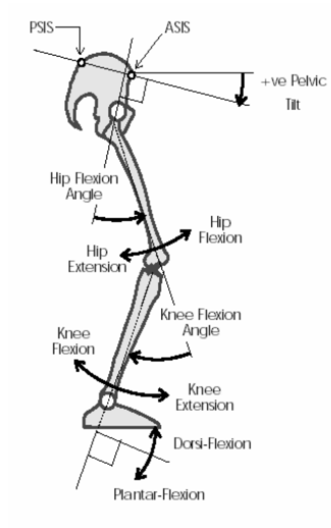
Rotation-Obliquity-Tilt is more appropriate to clinically describe pelvic attitude, but for the sake of standardization, the use of the existing sequence (TOR) is feasible. On the other hand, Schache et al. (2001) in a small sample of four healthy individuals performing self-paced running, found that even though lumbo-pelvic rotations approached 30° in amplitude, all Cardan angle sequences produced similar results, with a maximum rms between each sequence less than 7° for lumbar spine and 2.8° for pelvic rotations respectively. However, the author recognized that maximal absolute points did not occur simultaneously. The Cardan sequence which was used in this study, remains popular, facilitating comparison of results between authors. As it appears in the literature, in any calculation method of kinematic data, a dependence exists. The sequence dependency of Cardan/Euler angles is equivalent to the configuration dependence (the assumed shape of segments and type of joint) of the joint coordinate system (JCS) and the orientation dependence of the globographic angles (Baker 2011).

3.5.4 Pelvic Angles

Pelvic tilt is calculated about the laboratory's transverse axis, depending on the orientation of the subject in the laboratory. The sagittal pelvic axis, which is the anterior-posterior axis that crosses the waist markers and lies in the pelvis transverse plane, is projected into the laboratory sagittal plane. As measured by the PIG Model, pelvic tilt is the angle between the projected sagittal pelvic axis and the sagittal laboratory axis. When the posterior markers of the pelvis (PSIS) are higher than the anterior (ASIS), the tilt is positive, corresponding to the clinically defined anterior pelvic tilt.

Pelvic rotation is normally calculated about the frontal axis of the pelvic coordinate system and it is the angle between the sagittal axis of the pelvis and the sagittal laboratory axis, as projected in the pelvis transverse plane. When found to be negative (external), the opposite side is in front.

Pelvic obliquity is measured in the plane of the laboratory transverse axis (y-axis in standing and sitting postures) and the pelvic frontal axis (z-axis of the pelvis). Pelvic



obliquity is the angle between the projection into the plane of the transverse pelvic axis and projection into the laboratory transverse axis. When found to be negative, the opposite side of the pelvis is lower.According to the model, the pelvis is in neutral position having zero tilt, rotation and obliquity when all pelvic markers lay in the horizontal plane and the line that passes through both ASIS markers is parallel to a laboratory axis. With the pelvis in its neutral position, with its set of axis parallel to the laboratory axes, it is assumed to tilt about the transverse axis, rotate about its tilted sagittal axis, obtaining a pelvic obliquity, and finally rotating around its tilted and oblique frontal axis to obtain pelvic rotation. These angles of tilt, obliquity and rotation describe the orientation of the pelvis.

Fig. 3.9 Positive Pelvic Tilt. Source: Plug in Gait Manual
http://www.irc-web.co.jp/vicon_web/news_bn/PIGManualver1.pdf

3.5.5 Anterior Pelvic Plane acquisition

The data points we used for the description of the APP, as described in the literature, were acquired through manual palpation and pointing each anatomical landmarks (left and right ASIS and pubic symphysis) in each static posture, with a wand of total length 52.5cm with two collinear reflective markers of negligible weight. The 3-D position of the wand markers was recorded in Vicon Nexus and co-ordinates were acquired. The acquisition of the points that define the plane was performed by running the raw data file through a trigonometry based algorithm that was programmed in Matlab (script presented in the Appendix). The output from the Matlab script was run on ProCalc (Version 1.0, Vicon Motion Systems) to manually create the APP co-ordinate system, and produce kinematic data of the pelvic segment.

The coordinate system was defined in accordance with the PIG model's definition of the pelvic anatomical coordinate system, as well as with previous description of the APP coordinate system (Lin et al. 2011). The origin was taken to be the midpoint between the left and right ASIS. The Z-axis laid in the APP point upwards, the Y-axis was taken as pointing in the direction from the left ASIS to the right and the X-axis was pointed ventrally, perpendicular to the plane. The following step procedures were performed:

- A vector was defined in the direction from the left ASIS to the right.
- Another vector was defined in the direction from the pubic symphysis to the left ASIS.
- The midpoint point (M) of the LASIS, RASIS XYZ coordinates was calculated.
- A segment was created with origin at point M, the Y-axis was defined as the vector from the left ASIS to the right ASIS and the X-axis was the cross-product of the two vector defined previously.

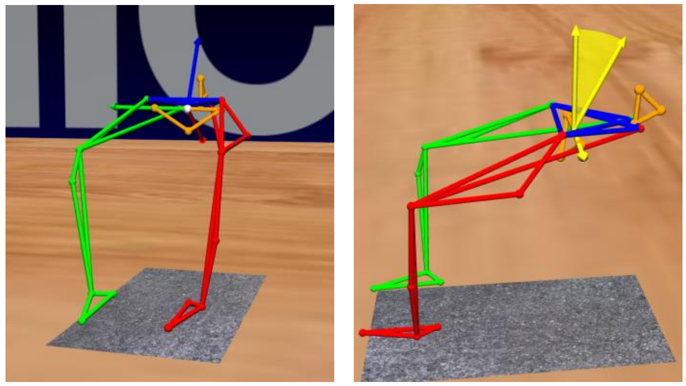


Fig 3.10 Left: Anatomical coordinate system of the Anterior Pelvic Plane. Right: APP sagittal tilt.

To calculate the tilt of the APP in the sagittal plane, we defined an angle between the segment’s Z-axis and the laboratory z-axis around the segment’s Y-axis, in the standing and sitting postures. In the lateral posture, the APP sagittal tilt angle was defined as the angle between the Z-axis of the segment and the laboratory x-axis, around the segment’s Y-axis. In the supine position, the sagittal tilt angle laid between the segment’s Z-axis and the lab’s x-axis around the segment’s Y-axis.

3.5.6 Pelvic tilt Acquisition

We created the pelvis segment and it is described in the “Local coordinate system” section of the Methodology. For the definition of the segment, we used the left and right posterior iliac spines (PSISs) and the right and left anterior superior iliac spines (ASISs) as registered with the wand. The points whose registration is achieved through palpation and direct pointing with the wand, are thought to be more reliable, since the problem of soft tissue artefact is partly resolved (Collins & Scholar 2003).

Pelvic tilt angle was defined as the angle of the X pelvic axis with the z-lab axis around Y pelvic axis in the supine position, while in the lateral position, it was specified as the opposite angle to the angle formed by between the X pelvic axis and the y-lab axis, around the Y pelvic axis. All the angles were defined as being about the LASIS-RASIS vector, so that the vertical axis would be projected on the anatomical sagittal plane. In this way, the position of the subject in space would not produce an error in the defined angles.

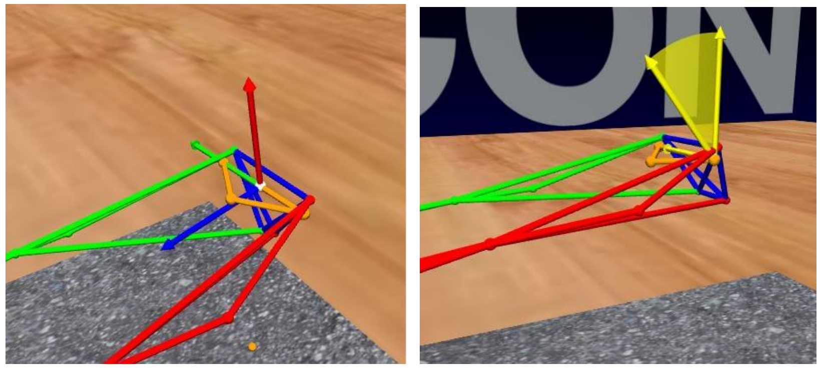


Fig. 3.11 Left: Supine position. The pelvic coordinate system created and visualized in Vicon ProCalc. The palpated ASIS points are marked orange, while the markers (LASI, RASI) are the points joined by the blue transverse line. Right: Positive pelvic tilt around the Y-axis; the ASIS are lower to the PSIS midpoint.

3.5.7 Comparison of Anterior Pelvic Plane Inclination angle to Pelvic Tilt angle

Based on the ISB recommended pelvic model (through the PIG marker configuration), the measured sagittal pelvic tilt is defined by the ASIS-PSIS inclination with the sagittal, around a medio-lateral axis, as described in the Methodology section. This angle is defined as positive (flexion angle), when the anterior markers (ASISs) are lower than the posterior (PSIS), while negative or extension pelvic tilt occurs when the situation is reversed. Anterior Pelvic Plane inclination in the sagittal axis is the representative of pelvic sagittal orientation or pelvic tilt. Whilst both angles are indicative of the same motion, they are defined based on different landmarks, so different numerical results are expected. (Kai et al. 2014) in an automatic construction of both anatomical coordinate systems (ACS) in a 3D bone model found that the ISB-recommended pelvic coordinate system showed significantly increased anterior tilt relative to the APP-defined tilt (range: 9.6-18.8°).

However since three landmarks in each case are used to define a segment, and no movement is considered to occur within the pelvis segment (Cappozzo et al. 1995), with the exception of potential deformation and of the oscillatory movement occurring in the sacroiliac joints (Floyd 2009), the relative position of the landmarks is not supposed to change. As a result, a linear relationship may exist in the sagittal APP inclination and pelvic tilt, which would possibly relate to bone geometry.

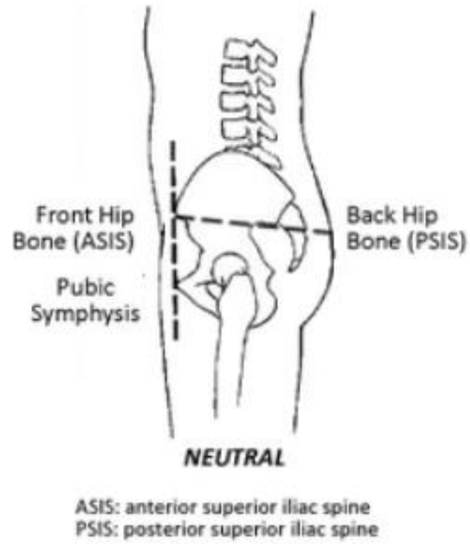


Fig.3.12: APP is represented by the sagittal line passing through the ASIS and the pubic symphysis, which is illustrated to be nearly vertical, while the ASIS-PSIS axis appears nearly horizontal. http://www.mybodyofknowledge.net/painrelief.html

3.6 Data points and Statistical Analysis

First, the aim was to ensure that the poses of the individuals were similar to allow further analysis. In the lateral decubitus position, the poses were characterized according to the angle of hip flexion of the right hip. Descriptive statistics of hip angles for the relative extension and the 30-degree flexed lateral position were calculated.

Pelvic tilt (PT), obliquity (Obl) and rotation (Rot) angles amongst individuals in the standing (STAND) and seated posture (SIT) were obtained by the PIG model. In the lateral and supine position, pelvic tilt was calculated, using the ASIS points, as registered with the wand, and the PSIS markers to build the pelvic coordinate system. The corresponding pelvic tilt angle was calculated through ProCalc, to follow the PIG model pelvic tilt definition. The PIG model was not used because of the definition of angles it uses, which do not comply with the lateral and supine position for reasons that are explained in a later section. The pelvic sagittal tilt (APPt) as calculated by APP angles to the global, was documented in each position.

- Normality of the data was checked through Anderson-Darling probability plots.
- Mean pelvic angles (tilt, obliquity, rotation) in standing and sitting postures from three trials were calculated for each individual (PIG output angles).
- Mean change in obliquity and rotation from standing to sitting were documented.
- Mean pelvic tilt (PT) in standing, sitting, lying postures was calculated and checked for statistical differences (PIG defined pelvic tilt angle and APP sagittal tilt, independently), through paired t-tests.
- Pelvic tilt of female (n=6) and male (n=6) participants in each posture, were drawn and compared through paired t-tests.
- Postural change in pelvic tilt was calculated and descriptive statistics drawn. A negative change describes the change towards posterior tilt, while this does not necessarily mean that the final tilt is posterior. Postural PT change (dPT) was compared between gender groups. The following comparisons were of interest:
    - Standing to sitting (SIT-STAND)
    - Supine to standing (STAND-SUP)
    - Supine to lateral (LAT-SUP)
    - Lateral to standing (STAND-LAT)
    - Supine to sitting (SIT-SUP)
- Normalized postural changes in pelvic tilt (PIG definition) and normalized postural changes in pelvic sagittal tilt (APP tilt) were compared, using Pearson's correlation test and linear regression analysis.

Minitab Statistics Software (Version 17) was used for statistical analysis and GraphPad Prism for graphical representation of data. Due to time constraints the lumbar spine tilt was not included in the analysis.

4 RESULTS

4.1 Sample

Initially, thirteen individuals volunteered for the project. Whilst satisfying the criteria, one of the subjects was excluded, due to excess soft tissue in the abdominal and lumbar area. Soft tissue did not allow correct placement of the pelvic markers and would potentially produce error due to soft tissue movement or loss of data, due to occlusion of the markers. The sample consisted of 12 participants (six male and six female), with a mean age of 30 years and a BMI of 22.7kg/m^2. Mean age and BMI was 33.5 years and 21.5kg/m^2 for the female group and 26.8 years and 23.8 kg/m^2 for the male group. There was no statistical difference between male and female BMI (p-value=0.263).

4.2 Positions

Between the two lateral postures only the flexed hip posture was analyzed because it was found to be more consistent in hip joint angle flexion between individuals. The range of hip angles was 9.32° to 38.05° in the flexed hip posture while -9.36° to 37.42° in the extended hip posture. Mean hip flexion angle of the posture analyzed was 26.89 ±7.3^o.

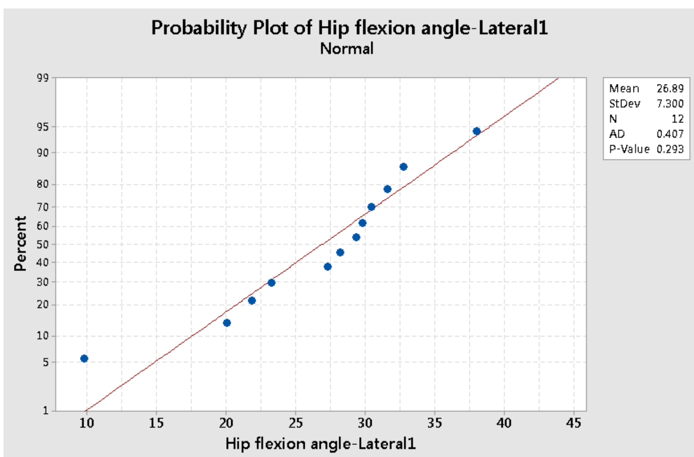


Fig 4.1 Probability Plot of Hip Flexion data. Descriptive statistic values are given in the r

4.3 Pelvic Tilt in different postures

Before proceeding to data analysis, normal distribution of the data was verified by performing the Anderson-Darling normality test. Comparison results of pelvic tilt (PT) between postures, and the respective results of APP sagittal inclination (APP) between the same postures are summarized in *Table 3.1*. Descriptive statistics are also presented in the table.

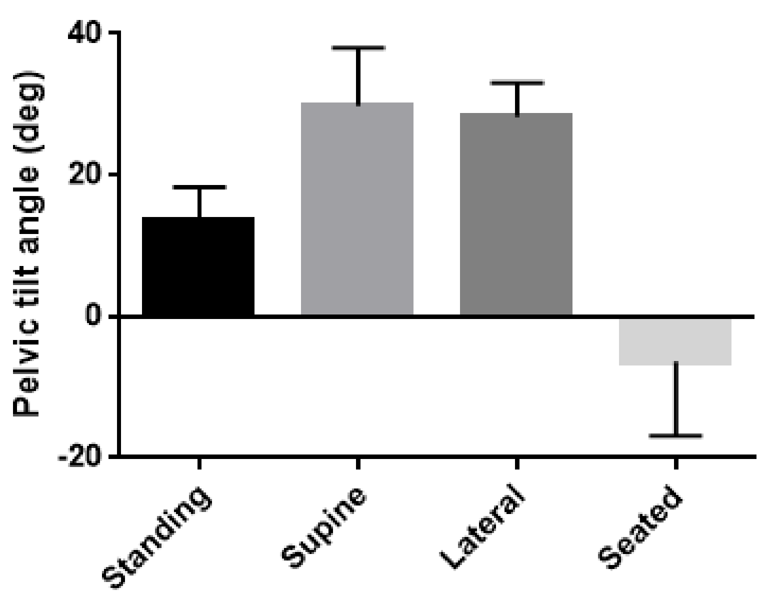
First, to avoid any confusion, the pelvic tilt angles as defined by the ISB recommendations, and the APP sagittal inclination angles will be described individually. Pelvic tilt is positive in the standing, supine and lateral position, as shown in *Table 4.1*. while in the seated position it shows a posterior tilt, which is consistent with the literature (Harrison et al. 1999). Supine and standing pelvic tilt were found to be statistically different ($p<0.01$). Seated pelvic tilt differed from any other posture ($p<0.01$).

The APP inclination angle was negative but variable in the standing and supine posture *(Table 4.1)*, while it had a high negative mean value of -29.76° in the sitting posture with a high standard deviation of 23.23° . In the lateral posture, the mean APP inclination angle was positive, indicating a flexion tilt, where iliac spines (ASIS) are anteriorly rotated relative to the pubic symphysis. Significant differences in the APP sagittal angle were noticed for the seated position, as related to the standing, lateral and supine decubitus position.

Overall, during standing, while pelvic tilt indicates a flexion sagittal tilt, APP inclination to the vertical is negative. In the supine posture, both angles indicate a flexion pelvic tilt. While the APP angles between supine and standing were compared and no statistical difference was found (p-value= 0.104), that was not the case with the mean pelvic tilt angles (ISB defined) (p-value< 0.001). In the seated posture, extension tilt is clearly observed, since means of both angles were found to be negative. In the lateral position, flexion pelvic tilt predominates, as documented by both the APP inclination angle and the pelvic tilt. Between lateral and supine posture, only the APP inclination angle was found to be statistically different.

Postures	Standing	Supine	Seated	Lateral
Standing	PT 14.07 ± 4.59 APP -2.84 ± 11.37	P-Value = 0.104 95% CI: (-1.19, 10.99)	*P-Value = 0.001 95% CI: (12.89, 40.96)	
Supine	*P-value= 0.000 95% CI: (11.19, 20.56)	PT 29.94 ± 8.56 APP 2.06 ± 7.91	*P-value= 0.000 95% CI: (21.07, 42.58)	*P-Value = 0.016 95% CI: (-11.76, -1.53)
Seated	*P-value = 0.000 95% CI: (14.25, 25.89)	*P-value= 0.000 95% CI: (27.65, 42.39)	PT -6.42 ± 10.52 APP -29.76 ± 23.23	
Lateral		P-Value = 0.655 95% CI: (-4.95, 7.53)		PT 28.65 ± 4.76 APP 8.71 ± 8.07

Table 4.1 Blue boxes: Paired t-test results for comparison of the Pelvic tilt between postures. Yellow boxes: Paired t-test results for comparison of the APP inclination between postures. Orange boxes: Means and standard deviations of pelvic tilt (PT) and APP sagittal inclination (APP) in each posture.



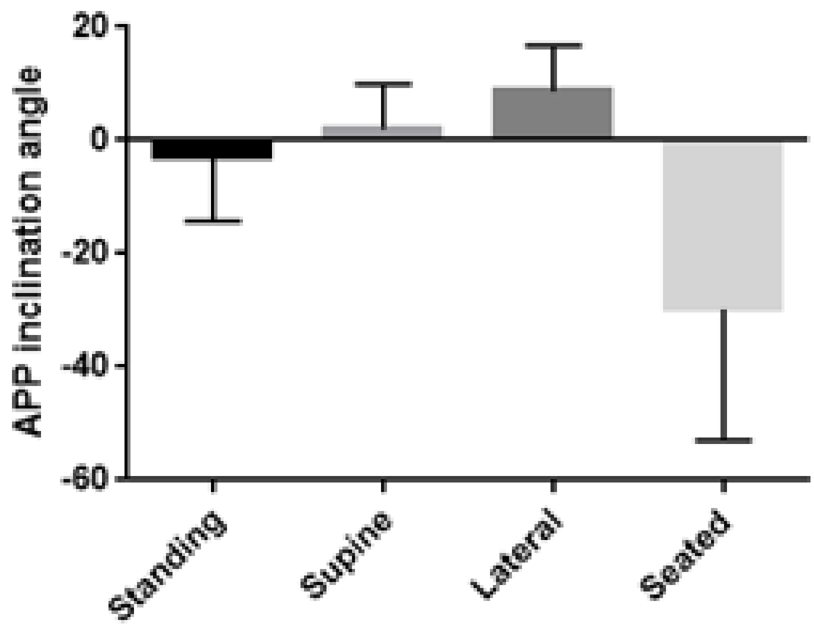


Fig 4.2-4.3 Mean and standard deviations of pelvic tilt and APP inclination angles in different postures

4.4 Postural Pelvic Tilt Change

The changes are summarized in the below figures, which show the boxplots of mean angle changes in all subjects due to postural shift. There is a clear change towards pelvic posterior tilt in the seated posture, shown in both figures *(4.4-4.5)*. Interpreting changes in APP inclination between different postures in our sample *(see figure 4.4)*, there is a negative change in pelvic tilt from the supine to the standing position. Practically, the pelvis has a tendency towards extension in the erect posture, as related to the supine posture. The opposite change seems to occur from the supine to lateral posture, where the pelvis tends to flex.

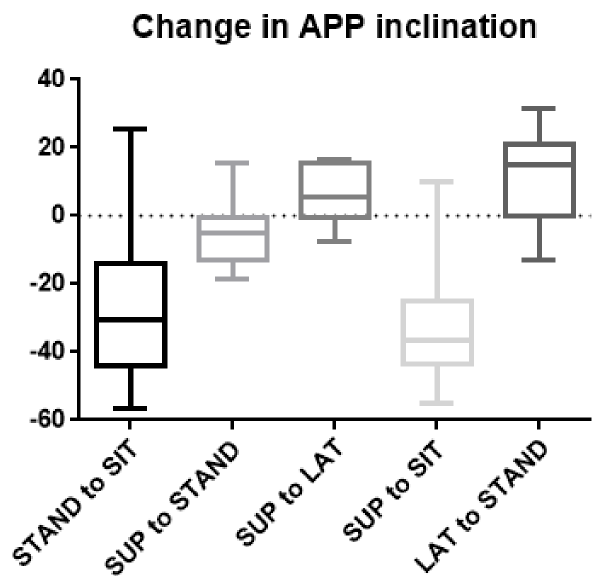


Fig 4.4 Boxplot of change in APP inclination angles (degrees) between postures

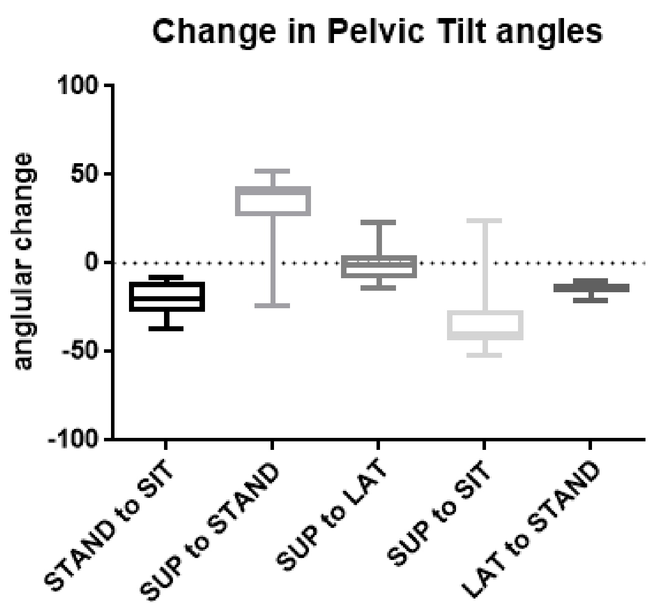


Fig. 4.5 Boxplots of mean changes in Pelvic tilt angles (degrees) between postures. Minimum, mean and maximum angle changes are presented.

Analyzing angular changes in pelvic tilt (ISB defined), from standing to sitting and from supine to sitting, there is an overall change posteriorly, towards extension. However, from supine to standing there is a change in pelvic tilt towards flexion *(see figure 4.5)*. Between the two methods of measuring sagittal inclination, the range of change in APP angles is obviously greater than that of the pelvic tilt angles.

Change in APP Inclination angle	Mean ± STDEV	Variance	Coefficient of Variance	Min angle difference	Max angle difference
Stand to Sitting	-26.93 ± 22.09	487.95	-82.04	-56.27	25.43
Supine to Standing	-4.90 ± 9.59	91.91	-195.75	-18.53	15.69
Supine to Lateral	6.65 ± 8.05	64.85	121.16	-7.36	16.69
Supine to Sitting	-31.82 ± 16.92	286.35	-53.17	-55.16	9.75
Lateral to Standing	11.54 ± 12.69	160.91	109.88	-13.18	31.34

Table 4.2 Descriptive statistics of change in APP inclination angle between postures.

Change in Pelvic Tilt angle	Mean ± STDEV	Variance	Coefficient of Variance	Minimum angle difference	Maximum angle difference
Stand to Sitting	-17.24 ± 13.45	180.84	-78.00	-35.95	16.57
Supine to Standing	32.34 ± 5.70	389.61	61.04	-24.13	51.51
Supine to Lateral	0.77 ± 11.37	129.35	1471.67	-13.59	23.45
Supine to sitting	-32.34 ± 19.74	389.61	-61.04	-51.51	24.13
Lateral to Standing	-14.573 ± 2.997	8.984	-20.57	-20.796	-10.498

Table 4.3 Descriptive statistics of change in Pelvic Tilt angle between postures

4.5 Pelvic Obliquity and Rotation in Standing and Sitting

It is easy to see that pelvic obliquity and rotation have small values and do not vary significantly between postures *(see figure 4.6)*. In our study, mean obliquity was found to be 0.861°±1.5 in standing and 0.759°±1.8 in sitting (p-value=0.820). Mean rotation was -0,477°±3,134 in standing and -1,837° ±2,308 in sitting (p-value=0.132).

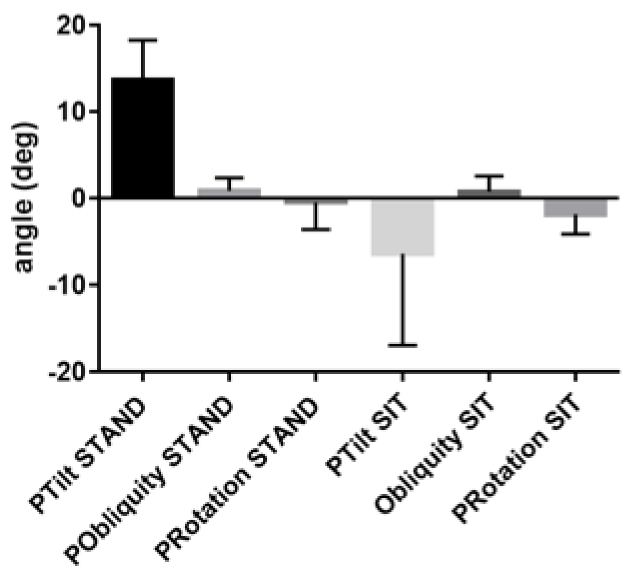


Fig. 4.6 Pelvic angles in standing and sitting presented with means and standard deviations.

4.6 Gender differences

We examined pelvic tilt and APP sagittal inclination angle between genders to determine if female and male individuals in our sample present significantly different pelvic tilt angles in each posture.

	Standing			Sitting			Supine	Lateral
Pelvic angles	Tilt	Obliquity	Rotation	Tilt	Obliquity	Rotation	Tilt	Tilt
Females (n=6)	15.65 ± 4.11	1.449 ± 0.766	0.27 ± 3.35	-0.47 ± 8.04	0.726 ± 1.34	-1.16 ± 1.50	30.23 ± 11.79	31.32 ± 0.77
Males (n=6)	11.64 ± 4.49	0.273 ± 1.881	1.22 ±3.01	-12.38 ± 9.67	0.792 ± 2.312	-2.52 ± 2.89	29.59 ± 3.03	25.12 ± 5.16
p-value	0.181	0.191	0.531	*0.042	0.934	0.391	0.821	*0.040

Table 4.4 Means and Standard deviations of pelvic tilt angles (degrees) according to posture and gender. t-test results of mean pelvic angles between genders in different postures. (*) indicates statistical difference.

APP tilt angle (deg)	Standing	Sitting	Supine	Lateral
Females	-1.77 ± 11.52	-14.80 ± 20.24	7.56 ± 5.66	13.62 ± 8.40
Males	-3.90 ± 12.21	-44.73 ± 15.49	-3.44 ± 5.76	3.80 ± 3.86
p-value	0.630	*0.002	*0.011	0.066

Table 4.5 t-test results of APP sagittal tilt angle (degrees) comparison between genders. (*) indicates statistical difference.

Overall, we observe that female subjects in our study present a more anterior pelvic tilt in all postures. However, it is not statistically different in the standing posture, where there was no observed difference between any pelvic angles (tilt, obliquity, rotation, APP sagittal tilt) of the two groups *(see tables 4.4-4.5)*. While seated, the male group showed a greater posterior tilt than women (p-value=0.042 and 0.002). Pelvic tilt angles presented significant differences between groups in the seated and lateral decubitus position *(table 4.4)*, while APP inclination angles were significantly different in the seated and supine position *(table 4.5)*. In the supine position, mean pelvic tilt angle is similar between both groups, with a higher standard deviation for women *(table 4.4)*. As for APP inclination in the same position, men show an extension tilt and women a flexion tilt *(table 4.5)*. Finally, in the lateral position, female pelves were more anteriorly tilted.

In the female group, we used Fischer Pairwise comparison (95%CIs) to determine differences between postures. Pelvic tilt angles in standing and sitting showed significant differences as related to the other postures. The same differences were presented in the men's group.

The APP inclination for the female group was significantly different in the seated and lateral decubitus posture, while in the male group only seated APP inclination differed to the other positions.

4.7 Comparison of pelvic tilt angles and APP inclination angles

Comparing angles, it is obvious that there is a statistical difference between the angle values. We performed correlation tests to examine the relationship of the values and found a Pearson correlation coefficient of 0.803 (p-value= 0.0), which represents a strong relationship between the defined angles.

Variables	Mean (StDev)	Variance	Coefficient of Variance	Minimum	Maximum
ISB angles	16.06 (16.46)	270.93	102.51	-21.16	43.73
APP angles	-5.54 (20.33)	413.12	-366.79	-68.78	28.22

Table 4.6 Descriptive statistics of angles in all postures.

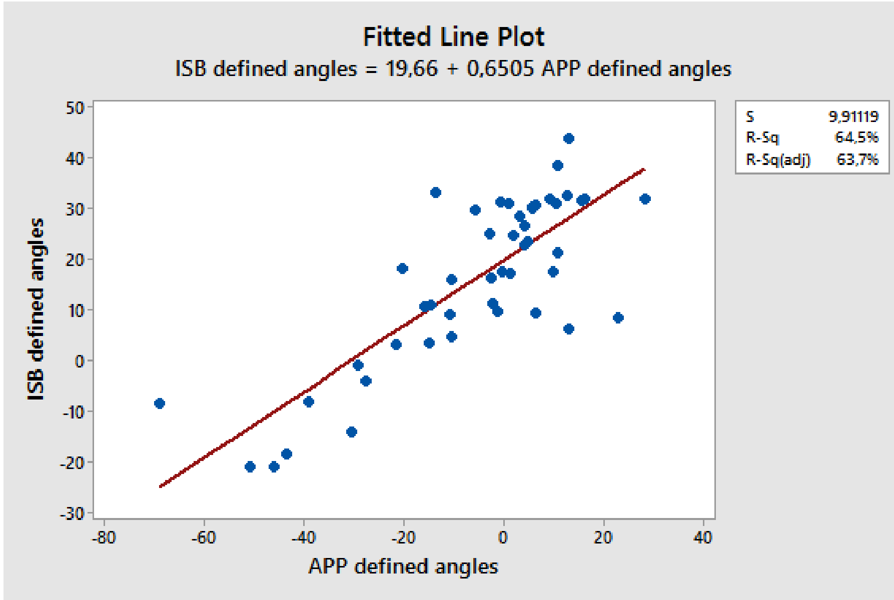


Fig.4.7 Regression analysis for APP inclination angle and pelvic tilt (ISB) angles in all the postures.

5. DISCUSSION

In this study we measured the pelvic sagittal orientation of twelve healthy individuals (1:1 male:female) in the standing, seated, supine and lateral decubitus position, using Vicon Motion capture system. The orientation was determined independently by two angles: pelvic tilt, as defined by the ISB recommendations and by Vicon Plug in Gait model and the APP inclination in the sagittal plane. We documented mean and standard deviation values of pelvic tilt for our sample in each posture, and examined if there are specific differences in pelvic orientation between postures. We examined gender differences in our sample. We also measured the mean difference in pelvic tilt induced by positional change. Finally, we used regression to state the linear relationship of APP inclination angles and pelvic tilt angles.

The first thing that is noticed in our data is the difference in pelvic tilt according to the method of anatomic coordinate system registration. The pelvis appears to be tilted more anteriorly when measured according to the ISB recommended pelvic tilt than if referred to the APP angle. These results are in accordance with a study by Kai et al. (2014), where the authors developed an algorithm for automatic construction of the anatomical coordinate system of the Lewinnek plane on CT-based 3D bone models and examined the potential differences caused by the selection of the coordinate system. They found a range of difference of 9.6-18.8°.

In standing, the mean APP inclination was found to be slightly negative (-2.84°±11.37°), indicating a position of the pelvis with the pubic symphysis being anterior to the anterior superior iliac spines. This result is comparable to the study by Philippot et al. (2009) et al where a mean APP inclination of -4° was documented, and Pinoit et al. (2007) who recorded a -1.7° APP tilt to the vertical. In the supine position the mean APP inclination angle was positive (2.06±7.91) but not statistically different (95%CI) to the standing angle (p-value=0.104). This finding is in accordance with the literature (Kyo et al. 2013).

In the seated posture, the pelvis had a posterior or extension tilt, described by a high negative APP tilt (-29.76°±23.23°), while the mean ISB-defined pelvic tilt for the same trials was -6.42°±10.52°. The shift to posterior tilt in the seated position is documented in the literature (Lazennec et al. 2004; Lazennec et al. 2015; Philippot et al. 2009). However, no studies with quantitative results on pelvic tilt (as defined by the APP inclination angle) on healthy individuals were found. Additionally, the APP angle in the seated position was found to have a significant difference as related to the same variable in other postures. This finding is in accordance with the study of Philippot et al. (2009) in 67 elder individuals. Moreover, we additionally measured the lateral decubitus position and found a statistically significant difference with the supine posture. This could be a point to consider in navigated THA surgery when registration of the plane is performed in the supine position and then the surgery performed in a lateral decubitus position.

In our study, APP angles in the standing posture ranged between -20.14° (extension tilt) to 13.05° (flexion tilt), while in the sitting posture our documented range of inclination was -68° to 23°. In the literature there exist even higher positive range of values, while the posterior tilt of 68° is an untypical finding. Stephens et al. (2015) documented a range of -30° to 21.5° APP defined pelvic tilt in the standing posture and a range of -48° to 42° in the seated posture. However, their study was performed radiographically in osteoarthritis patients. Kanawade et al. (2014) found a pelvic tilt range of 40° in standing, which is higher than in our study, and 42° in the seated posture, which is a lower range compared to our study. However, these researchers radiographically measured a sample of 85 osteoarthritis patients, so it is reasonable to have different results. In an EOS study of Lazennec et al. (2015), in a cohort of 269 total hip replacement, the APP inclination in standing was found to be 0.9°±8.6° and 23°±13° in sitting. No comparisons can be drawn, mainly because of the different methodology, different sample size and characteristics (age, pathology, BMI, level of activity etc.).

As for differences in APP inclination with change in posture, we recorded a change towards posterior tilt (-4.9°±9.59°) from the supine position to the erect posture. Similar findings have been previously documented in THA patients preoperatively (Nishihara et al. 2000; Parratte et al. 2009; Taki et al. 2012). The opposite seemed to occur in the transition from supine to lateral decubitus, where the pelvis tends to flex (6.65°±8.05°).

As for gender differences in our sample, overall female participants had a greater anterior tilt in all postures. However, in the standing posture this difference was not statistically important. In the seated position, the male group showed a greater posterior tilt (males: -44.73°± 15.49°; females: -14.80° ± 20.24°). In the supine position, male pelves were more extended than female. In the lateral decubitus, female pelves were more flexed. There are confounding factors in this comparison, since the female group was relatively older. Moreover, our sample was small to draw more conclusions.

Comparing APP defined pelvic tilt to ISB defined pelvic tilt, the former showed higher variance in our measurements with a range from -68.78° to 43.73°, while the ISB defined range of measurement was -21.16° to 43.73°. A positive linear relationship was found ($r=0.803$, p-value<0.01). Rousseau et al (2009) justified the variability in APP inclination as caused by morphological variations of the configurations of the iliac bones, which relate to inter-individual variability but not much to pelvic orientation. Future research may elucidate this point.

There were several limitations in our study. First, our sample is small (n=12) and is not expected to be representative of the general population, since participants were recruited from the university. As for our methodology, the pelvis segment was regarded as a rigid body so that pelvic kinematics can be calculated. It is assumed that no movement occurs within the pelvis. This cannot be confirmed or measured. In this particular study, where the person is measured while being seated or lying, there are some direct forces acting on the pelvis, due to weight bearing. As a result, a temporary deformation of the pelvic girdle may occur in these postures.

As for our experimental protocol, the registration of the APP anatomical landmarks was performed with the wand in a static position. The subject was asked to remain completely still, until registration of all points was completed. The researcher would palpate and point with the wand the right anterior superior iliac spine, then the left anterior superior iliac spine and in the end the pubic symphysis. Although the registration of all three points should represent the same static segment orientation, registration of the points could not be performed simultaneously and some degree of movement is thought to have occurred during the procedure. This would produce an error in the calculated APP co-ordinate system and sagittal inclination angle. Movement may have occurred either spontaneously by the subject or due to the pressure applied to the pelvis by the researcher in order to locate the bony landmarks. Efforts were made to minimize this movement. However, the standing position is regarded as the most unstable position, since the person needs to resist against the pressure exerted on one, while being instructed to maintain one's natural comfortable posture. The muscular contraction that may occur, may also affect the standing posture. Also, the quality of posture may have been affected by the individual feeling uncomfortable during palpation and especially because registration of the points is performed just once in each posture and the individual is not given time to familiarize with the procedure.

We need to acknowledge the distinction between the bony APP and the soft tissue APP, when bony landmarks are palpated and registered over soft tissue. In this study, the registration was performed externally and not directly on bone. The researcher's aim was to point the landmarks with the wand as close to the bone as possible. Wolf et al. (2005) made a distinction between the bony APP and the soft tissue APP. The orientation of the plane may be falsely calculated due to varying soft tissue thickness covering the landmarks. Therefore, we acknowledge that bony APP may not be well represented by our measurements. However, since registration of the APP in navigated THA is usually executed by pointing with the wand, it does not seem unreasonable to study the APP as defined indirectly over soft tissue.

Another limitation in this study is that the registration of the bony landmarks of the APP, as well as of the posterior superior iliac spines (in the supine position), was performed once by a single examiner. Therefore, due to the rater's bias, the data acquired may not be completely reliable. The PSISs in the supine position were palpated and registered through pointing with the wand. The researcher could not visually inspect the points but relied completely on palpation. This is identified as a potential source of error.

Finally, we did not study the three-dimensional orientation of the pelvis nor the orientation of the lumbar segment relative to the pelvis, as initially planned due to time constraints. While the pelvic obliquity and rotation in the standing and sitting posture are quite small, they are calculated out of a Cardan angle sequence where pelvic tilt is calculated first, whilst the rotation about the other axes (obliquity and rotation) follows as described in the method section. As a result, obliquity and rotation are compromised due to the selection of the sequence. While there were various researchers trying to elucidate which sequence works better in a sense of giving more clinically related results, the rotation-obliquity-tilt sequence seems more reasonable (Baker 2001). For the standing and seated posture, we used the PIG sequence because it is practical and more widely used. In the lateral and supine decubitus, only pelvic tilt angle was calculated. In order to account for the person's orientation in the lab, the angles were calculated using the projected the lab axis on the sagittal body plane.

6. CONCLUSIONS

In this study, we documented the variations of pelvic tilt in normal individuals in the standing, seated, supine and lateral decubitus position with relative flexion of the hips. We measured the anterior pelvic plane inclination angle and the pelvic tilt angle as defined by the ISB recommendation in 12 individuals, between postures and documented the mean changes in pelvic tilt between positions. Comparisons were drawn with respect to posture, gender and measured angle. The relationship between ISB and APP defined pelvic tilt was examined among all postures.

Our results indicate how pelvic tilt values change according to the anatomical coordinate system used. Pelvic tilt angles defined by the ISB recommendations presented a greater anterior tilt as compared to APP tilt angles, in all postures. Given that posterior pelvic tilt is associated with a vertical malpositioning of the cup and high risk of impingement and excessive wear, defining pelvic tilt according to the ISB standards for pre-operative assessment of the patients might have catastrophic effect, if the difference between the two angles is not taken into consideration.

In general, we found that pelvic tilt was variable between individuals in the natural standing posture. The APP plane was located slightly posterior to the vertical indicating a posterior pelvic tilt. In the supine position, the pelvic tilt was anterior, indicating a posterior rotation of the pelvis when the person rises from supine to standing. The amount of this posterior change in pelvic tilt is particularly important in THA patients, because it is predictive of the change in acetabular inclination and anteversion of the cup, from an operative position to a functional position. In our sample of healthy and young subjects, this change was not statistically significant, but changes may be intensified in presence of spinal and hip pathology in older adults.

In the sitting posture, an increased posterior tilt was found, especially in the male group, as defined by both angles. The posterior pelvic tilt in this posture indicates that this functional position is particularly dangerous for hip dislocation. In gender comparisons we found an increased anterior tilt of the female pelvis.

Finally, we determined a strong linear relationship between these angles, derived through regression analysis. Also, a higher variability in APP inclination angles as compared to the ISB angles was noticed.

Further research is needed to define a clinical measure of pelvic tilt that can both serve navigation in surgery, but also bring less variable results. For this reason, it is the researcher's opinion that the incorporation of morphological parameters (S1 sacral slope or pelvic incidence) in anterior pelvic plane inclination (APP) angle may bring more consistent results in the measurement of pelvic orientation.

Further research on changes in lumbo-pelvic kinematics and spino-pelvic parameters with an emphasis on different postures and daily activities is still required to help identify the postural and temporal changes that are associated with total hip replacement. Motion capture systems can serve for this purpose, since it does not involve exposure to ionizing radiation or invasive procedures. However, a lack of relevant research was observed.

Knowledge on these fields has the potential to reduce complications by introducing a more precise and individualized pre-operative planning and can therefore bring more functional results in total hip arthroplasty.

REFERENCES

Asayama, I. et al., 2004. Intraoperative pelvic motion in total hip arthroplasty. *The Journal of arthroplasty*, 19(8), pp.992–997.

Babisch, J.W., Layher, F. & Amiot, L.-P., 2008. The rationale for tilt-adjusted acetabular cup navigation. *The Journal of bone and joint surgery. American volume*, 90(2), pp.357–365.

Baker, R., 2011. Globographic visualisation of three dimensional joint angles. *Journal of Biomechanics*, 44(10), pp.1885–1891. Available at: http://dx.doi.org/10.1016/j.jbiomech.2011.04.031.

Baker, R., 2001. Pelvic angles: A mathematically rigorous definition which is consistent with a conventional clinical understanding of the terms. *Gait and Posture*, 13(1), pp.1–6.

Barbier, O. et al., 2014. The reliability of the anterior pelvic plane for computer navigated acetabular component placement during total hip arthroplasty: Prospective study with the EOS imaging system. *Orthopaedics & Traumatology: Surgery & Research*, 100(6), pp.S287–S291. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1877056814001509.

Beckmann, J. et al., 2009. Cup positioning in THA: Current status and pitfalls. A systematic evaluation of the literature. *Archives of Orthopaedic and Trauma Surgery*, 129(7), pp.863–872.

Bohrani, M., McGregor, A. & Bull, A.M.., 2013. An alternative technical marker set for the pelvis is more repeatable than the standard marker set. *Gait and Posture*.

Cappozzo, a. et al., 1995. Position and orientation in space of bones during movement: Anatomical frame definition and determination. *Clinical Biomechanics*, 10(4), pp.171–178.

Cole, G.K. et al., 1993. Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. *Journal of biomechanical engineering*, 115(4A), pp.344–349.

Collins, M.M. & Scholar, M., 2003. Validation of a Protocol for Motion Analysis. , 370(6), pp.84–90.

Dandachli, W. et al., 2013. The influence of pelvic tilt on acetabular orientation and cover: A three-dimensional computerised tomography analysis. *HIP International*, 23(1), pp.87–92.

Davis, R.B. et al., 1991. A gait analysis data collection and reduction technique. *Human Movement Science*, 10(5), pp.575–587.

DiGoia, A. et al., 2006. Functional pelvic orientation measured from lateral standing and sitting radiographs. *Clin Orthop Relat Res*.

Floyd, R.., 2009. The Hip joint and Pelvic Girdle. In *Manual Of Structural kinesiology*.

Franklin, M.E. & Conner-Kerr, T., 1998. An analysis of posture and back pain in the first and third trimesters of pregnancy. *The Journal of orthopaedic and sports physical therapy*, 28(3), pp.133–138. Available at: http://www.ncbi.nlm.nih.gov/pubmed?term=(((lumbar) AND posture) AND pelvic tilt) AND pregnancy.

Goel, A. et al., 2014a. Dislocation Rates Following Primary Total Hip Arthroplasty Have Plateaued in the Medicare Population. *The Journal of Arthroplasty*, 30(5), pp.743–746. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0883540314008882.

Goel, A. et al., 2014b. Dislocation Rates Following Primary Total Hip Arthroplasty Have Plateaued in the Medicare Population. *The Journal of Arthroplasty*, 42(October 2005), pp.32–35. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0883540314008882.

Grammatopoulos, G. et al., 2014. Pelvic position and movement during hip replacement. *The Bone & Joint Journal*, pp.876–883.

Grood & Suntay, 1983. A joint coordinate system for the clinical description of Three-dimensional motions: an application to the knee. *Journal of Biomechanical Engineering*, 105.

Harrison, D.D. et al., 1999. Sitting biomechanics part I: review of the literature. *Journal of manipulative and physiological therapeutics*, 22(9), pp.594–609.

Kadaba, M.P., Ramakrishnan, H.K. & Wootten, M.E., 1990. Measurement of lower extremity kinematics during level walking. *Journal of Orthopaedic Research*, 8(3), pp.383–392.

Kai, S. et al., 2014. Automatic construction of an anatomical coordinate system for three-dimensional bone models of the lower extremities - Pelvis, femur, and tibia. *Journal of Biomechanics*, 47(5), pp.1229–1233. Available at: http://dx.doi.org/10.1016/j.jbiomech.2013.12.013.

Kalteis, T. et al., 2006. Imageless navigation for insertion of the acetabular component in total hip arthroplasty: is it as accurate as CT-based navigation? *The Journal of bone and joint surgery. British volume*, 88(2), pp.163–167.

Kanawade, V., Dorr, L. & Wan, Z., 2014. Predictability of Acetabular Component Angular Change with Postural Shift from. *The Journal of Bone and Joint Surgery*, pp.978–986.

Kennedy, J.G. et al., 1998. Effect of acetabular component orientation on recurrent dislocation, pelvic osteolysis, polyethylene wear, and component migration. *Journal of Arthroplasty*, 13(5), pp.530–534.

Kisho Fukuchi, R. et al., 2010. Evaluation of alternative technical markers for the pelvic coordinate system. *Journal of Biomechanics*, 43(3), pp.592–594. Available at: http://dx.doi.org/10.1016/j.jbiomech.2009.09.050.

Kotwal, R.S. et al., 2009. Outcome of treatment for dislocation after primary total hip replacement. *The Journal of bone and joint surgery. British volume*, 91(3), pp.321–326.

Krenzel, B. a. et al., 2010. High preoperative range of motion is a significant risk factor for dislocation in primary total hip arthroplasty. *Journal of Arthroplasty*, 25(SUPPL. 6), pp.31–35. Available at: http://dx.doi.org/10.1016/j.arth.2010.04.007.

Kyo, T., Nakahara, I. & Miki, H., 2013. Factors predicting change in pelvic posterior tilt after THA. *Orthopedics*, 36(6), pp.e753–9. Available at: http://www.ncbi.nlm.nih.gov/pubmed/23746037.

Lazennec, J. et al., 2015. Total Hip Prostheses in Standing , Sitting and Squatting Positions : An Overview of Our 8 Years Practice Using the EOS Imaging Technology. , pp.26–44.

Lazennec, J.Y. et al., 2011. Acetabular anteversion with CT in supine, simulated standing, and sitting positions in a THA patient population. *Clinical Orthopaedics and Related Research*, 469(4), pp.1103–1109.

Lazennec, J.Y. et al., 2004. Hip-spine relationship: A radio-anatomical study for optimization in acetabular cup positioning. *Surgical and Radiologic Anatomy*, 26(2), pp.136–144.

Legaye, J., 2009. Influence of the sagittal balance of the spine on the anterior pelvic plane and on the acetabular orientation. *International Orthopaedics*, 33(6), pp.1695–1700.

Lembeck, B. et al., 2005. Pelvic tilt makes acetabular cup navigation inaccurate. *Acta orthopaedica*, 76(4), pp.517–523.

Levine, D., Richards, J. & Whittle, M.W., 2012. *Whittle's Gait Analysis*, Churchill Livingstone.

Lewinnek, G. et al., 1978. Dislocations after total hip-replacement arthroplasties. *J Bone Joint Surg*.

Lin, F. et al., 2011. Limitations of Imageless Computer-Assisted Navigation for Total Hip Arthroplasty. *Journal of Arthroplasty*, 26(4), pp.596–605. Available at: http://dx.doi.org/10.1016/j.arth.2010.05.027.

Magee, D.J., 2008. *Orthopedic Physical Assessment* Elsevier Health Sciences, ed., Martini, F.H., Nath, J.L. & Bartholomew, E.F., 2012. *Martini fundamentals of anatomy and physiology* 9th ed.,

McClelland, J. a. et al., 2010. Alternative modelling procedures for pelvic marker occlusion during motion analysis. *Gait and Posture*, 31(4), pp.415–419. Available at: http://dx.doi.org/10.1016/j.gaitpost.2010.01.004.

McCollum, D. & Gray, W., 1990. Dislocation after total hip arthroplasty. Causes and prevention. *Clin Orthop Relat Res*. Available at: http://www.ncbi.nlm.nih.gov/pubmed/2245542.

Miki, H. et al., 2014. Risk of edge-loading and prosthesis impingement due to posterior pelvic tilting after total hip arthroplasty. *Clinical Biomechanics*, 29(6), pp.607–613. Available at: http://dx.doi.org/10.1016/j.clinbiomech.2014.05.002.

Mörl, F. & Blickhan, R., 2006. Three-dimensional relation of skin markers to lumbar vertebrae of healthy subjects in different postures measured by open MRI. *European Spine Journal*, 15(6), pp.742–751.

Moskal, J.T. & Capps, S.G., 2011. Acetabular Component Positioning in Total Hip Arthroplasty: An Evidence-Based Analysis. *The Journal of Arthroplasty*, 26(8), pp.1432–1437. Available at: http://dx.doi.org/10.1016/j.arth.2010.11.011.

Murray, D.W., 1993. the Definition and Orientation Measurement of. *British Editorial Society Of Bone and Joint Surgery*, pp.228–232.

Nishihara, S. et al., 2000. MEASUREMENTS OF PELVIC FLEXION ANGLE IN DIFFERENT POSTURES USING 3D-CT RECONSTRUCTION OF THE 46th Annual Meeting , Orthopaedic Research Society , March 12-15 , 2000 , Orlando , Florida. , p.6879.

Padgett, D. & Warashina, H., 2004. The unstable total hip replacement. *Clin Orthop Relat Res*.

Parratte, S. et al., 2009. The 2008 frank stinchfield award: Variation in postoperative pelvic tilt may confound the accuracy of hip navigation systems. *Clinical Orthopaedics and Related Research*, 467(1), pp.43–49.

Parratte, S. et al., 2008. The use of ultrasound in acquisition of the anterior pelvic plane in computer-assisted total hip replacement: a cadaver study. *The Journal of bone and joint surgery. British volume*, 90(2), pp.258–263.

Parratte, S. & Argenson, J., 2007. Validation and usefulness of a computer-assisted cup-positioning system in total hip arthroplasty. A prospective, randomized, controlled study. *J Bone Joint Surg Am*, 89, p.494.

Parratte, S., Aubaniac, J.M. & Argenson, J.N., 2008. Computer-assisted cup positioning in total hip arthroplasty: Usefulness, limits and future. *Interactive Surgery*, 3(3), pp.148–153.

Perkins, N., 2013. Publication Summary Scottish Arthroplasty Project. , 2013(Section 4), pp.5–6.

Philippot, R. et al., 2009. Pelvic balance in sagittal and Lewinnek reference planes in the standing, supine and sitting positions. *Orthopaedics and Traumatology: Surgery and Research*, 95(1), pp.70–76.

Pierchon, F. et al., 1994. Causes of dislocation of total hip arthroplasty. CT study of component alignment. *J Bone Joint Surg Br.*, 76(1).

Pinoit, Y. et al., 2007. Low accuracy of the anterior pelvic plane to guide the position of the cup with imageless computer assistance: variation of position in 106 patients. *Rev Chir Orthop*, 93.

Rajesh, M., 2012. *Mastering Orthopedic Techniques Total Hip Arthroplasty*,

Richolt, J., Effenberger, H. & Rittmeister, M., 2005. How does soft tissue distribution affect anteversion accuracy of the palpation procedure in image-free acetabular cup navigation? An ultrasonographic assessment. *Comput Aided Surg*, 10(2), pp.87–92. Available at: http://www.ncbi.nlm.nih.gov/pubmed/16298919.

Rousseau, M. et al., 2009. Optimization of Total Hip Arthroplasty Implantation Is the Anterior Pelvic Plane Concept Valid ? *Journal of Arthroplasty*, 24(1), pp.22–26. Available at: http://dx.doi.org/10.1016/j.arth.2007.12.015.

Roussouly, P. & Pinheiro-Franco, J.L., 2011. Biomechanical analysis of the spino-pelvic organization and adaptation in pathology. *European Spine Journal*, 20, pp.1–10.

Sanz-Reig, J., Lizaur-Utrilla, a. & Miralles-Muñoz, F., 2015. Risk factors for total hip arthroplasty dislocation and its functional outcomes. *Revista Española de Cirugía Ortopédica y Traumatología (English Edition)*, 59(1), pp.19–25. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1988885614001278.

Schache, a G. et al., 2001. The effect of differing Cardan angle sequences on three dimensional lumbo-pelvic angular kinematics during running. *Medical engineering & physics*, 23(7), pp.493–501.

Schmalzried, T.P., 2009. The Importance of Proper Acetabular Component Positioning and the Challenges to Achieving It. *Operative Techniques in Orthopaedics*, 19(3), pp.132–136. Available at: http://dx.doi.org/10.1053/j.oto.2009.09.008.

Stem, E. et al., 2006. Computed tomography analysis of acetabular anteversion and abduction. *Skeletal Radiology*.

Stephens, A. et al., 2015. The kinematic relationship between sitting and standing posture and pelvic inclination and its significance to cup positioning in total hip arthroplasty.

International Orthopaedics, 39(3), pp.383–388. Available at: http://link.springer.com/10.1007/s00264-014-2491-y.

Taki, N. et al., 2012. Change in Pelvic Tilt Angle 2 to 4 Years After Total Hip Arthroplasty. *The Journal of Arthroplasty*, 27(6), pp.940–944. Available at: http://dx.doi.org/10.1016/j.arth.2011.10.003.

Tamura, S. et al., 2014. Spinal Factors Influencing Change in Pelvic Sagittal Inclination From Supine Position to Standing Position in Patients Before Total Hip Arthroplasty. *The Journal of Arthroplasty*, 29(12), pp.2294–2297. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0883540313008590.

Tiberi, J. V. et al., 2015. What Is the Fate of THA Acetabular Component Orientation When Evaluated in the Standing Position? *The Journal of Arthroplasty*, pp.1–6. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0883540315002235.

Vogt, L. et al., 2003. Cross-validation of marker configurations to measure pelvic kinematics in gait. *Gait and Posture*, 18(3), pp.178–184.

Van Wingerden, J., Vleeming, A. & Ronchetti, I., 2008. Differences in standing and forward bending in women with chronic low back or pelvic girdle pain: indications for physical compensation strategies. *Spine (Phila Pa 1976)*, 33(11), pp.334–41. Available at: http://www.ncbi.nlm.nih.gov/pubmed/18469680.

Wolf, A. et al., 2005. A kinematic model for calculating cup alignment error during total hip arthroplasty. *Journal of Biomechanics*, 38(11), pp.2257–2265.

Wu, G. & Cavanagh, P.R., 1995. Isb Recommendations in the Reporting for Standardization of Kinematic Data. *J Biomechanics*, 28(10), pp.1257–1261.

Yarlagadda, R. & Jones, S. a., 2009. (v) The management of dislocation in hip arthroplasty. *Orthopaedics and Trauma*, 23(5), pp.335–341. Available at: http://dx.doi.org/10.1016/j.mporth.2009.08.011.

Ybinger, T. et al., 2007. Accuracy of Navigation-Assisted Acetabular Component Positioning Studied by Computed Tomography Measurements. Methods and Results. *Journal of Arthroplasty*, 22(6), pp.812–817.

Yoon, Y.S. et al., 2008. Resolving inconsistencies in defining the target orientation for the acetabular cup angles in total hip arthroplasty. *Clinical Biomechanics*, 23(3), pp.253–259.

APPENDIX

ADVERTISING EMAIL

Hello,

Are you a healthy adult with a BMI<30 and no musculoskeletal conditions? If so we would like to invite you to participate in our motion analysis study.

We are researchers from the Biomedical Engineering Department and the project we have undertaken is the Assessment of composite movements between the spine, pelvis, hip knee and ankle in different postures of daily activities in normal persons.

This project is being led by Mr Jon Clarke who is an orthopedic surgeon and lecturer in the department, Dr Angela Deakin who is a Honorary research fellow and Panagiota Vlaserou who is a postgraduate student and a physiotherapist.

In this study, we will measure each subject's pelvic orientation related to the orientation of other body segments in the Vicon workstation in the Biomechanics lab. We will attach markers to anatomical landmarks on each subject's body and measure their position in different static postures. The investigation will be a single session and won't last over an hour.

The aim is to provide information that would lead to a more individualized approach in Total Hip Arthroplasty (THA). Practical knowledge on the variations of pelvic orientation, among individuals and among different postures, is valuable in this field and the incorporation of this knowledge in the planning and execution of the surgery can bring a more functional postoperative outcome.

We would be extremely grateful if you would consider participating. In this case, contact us to provide further information, the Participant Information Sheet (PIS), which you should read before you agree to participate in this investigation:

Panagiota.vlaserou.2014@uni.strath.ac.uk (Panagiota Vlaserou)

Jon.clarke@strath.ac.uk (Mr Jon Clarke)

If you have any questions do not hesitate to contact us.

Thank you very much for your time!

ETHICS APPLICATION FORM AND PIS FORM

Only part of the Ethics Application form is attached. In case more information is needed, please communicate with the Department of Biomedical Engineering of the University of Strathclyde.

Ethics Application Form

Please answer all questions

6. Location of the investigation
At what place(s) will the investigation be conducted Department of Biomedical Engineering Biomechanics Laboratory University of Strathclyde Wolfson Building 106 Rottenrow Glasgow
If this is not on University of Strathclyde premises, how have you satisfied yourself that adequate Health and Safety arrangements are in place to prevent injury or harm? N/A

7. Duration of the investigation
Duration(years/months) : 7 weeks Start date (expected): 22 / 06 / 2015 Completion date (expected): 07 / 08 / 2015

8. Sponsor Please note that this is not the funder; refer to Section C and Annexes 1 and 3 of the Code of Practice for a definition and the key responsibilities of the sponsor.
Will the sponsor be the University of Strathclyde: Yes ☒ No ☐ If not, please specify who is the sponsor:

9. Funding body or proposed funding body (if applicable) – N/A
Name of funding body: Status of proposal – if seeking funding (please click appropriate box): ☐ In preparation ☐ Submitted ☐ Accepted Date of submission of proposal: / / Date of start of funding: / /

10. Ethical issues
Describe the main ethical issues and how you propose to address them: The subjects have to wear tight-fitting clothes, with their skin exposed as much as possible. The subject should not wear a top, other than a sports bra (females). Clothing can interfere with measurements in 3D video analysis and give inaccurate results. The participants will be informed through the PIS document about this and if feeling uncomfortable, they may anytime leave. The subject may feel uncomfortable because a marker should be attached on the pubic symphysis. Since the project has clinical relevance to total hip arthroplasty, the reference system which is used in clinical practice should also be registered in this particular study, for reasons of comparison. To be more precise, there is the need to register the Anterior Pelvic Plane, which is currently the reference plane in navigated surgery used to guide the surgeons during arthroplasty. Three points on the anterior aspect of the pelvis are required to locate this plane. There is no other method to register this plane and a simulator of this region would produce undesirable high variability in the results. The problem is addressed by priori informing the participants and by the discreet behaviour of the researchers. The investigator needs to handle the subjects to bring them in the correct position, if needed: A surgical position needs to be simulated, in order to provide information about the orientation of the pelvis in space in the lateral decubitus position in surgery. Small variations in the flexion of the hips or trunk can make a difference in the pelvic tilt. The pose will be first described, the subject will be given oral directions and if appropriate, the researcher will manually help/correct the position of the subject. In order to be precise and fast, so that the procedure does not become uncomfortable for the participants, the laboratory will be set up in advance and the researchers will be also prepared with the specific skills needed.

11. Objectives of investigation (including the academic rationale and justification for the investigation) Please use plain English.
By recording the position of the markers on the body of the subjects in different postures of daily life, the aim is to investigate the relationship between the orientation of body segments (spine, hip, knee, ankle) and the orientation of the pelvis, among individuals and among different postures. Also, we will measure the position of the anterior pelvic plane in three-dimensional space and how it relates to the pelvic orientation we found. This information is clinically useful for total hip arthroplasty (THA) planning. Variations in pelvic orientation should be a factor taken into consideration in the preoperative planning of THA. The incorporation of individual pelvic tilt may provide a more functional outcome with less complications, such as instability, dislocation and impingement, which are main concerns in THA. The key factors is that the orientation of the upper segment (cup) of the artificial joint needs to be positioned correctly to allow functional weight-bearing and range of motion of the joint. The position of this segment is a major risk factor for dislocation. However, current techniques to find the optimal orientation and perform the

positioning of the cup do not take into account how the pelvis changes position among activities and postures and how it varies among individuals. Nevertheless, there is a consent in the literature that pelvic motion will eventually affect the functional position of the cup. Our research deals with pelvic orientation and its relationship with other body segments.

12. Participants

Please detail the nature of the participants:
Healthy, normal volunteers of either sex with no history of physical, cognitive or neurological disorders.
Summarise the number and age (range) of each group of participants:
Number: **30** Age (range): **≥20 years old**
Please detail any exclusion criteria and any further screening procedures to be used:
BMI ≥ 30
Chronic or acute pain
inhibition syndromes/ musculoskeletal conditions
Allergies to adhesive tape/ history of skin allergies
Inability to stand, walk, sit on a chair, lie supine and on the side unassisted
Being pregnant or having recently given birth
Former orthopaedic surgery
Visual/ hearing impairment that obstructs the person from following directions (or which may interfere with the subject's standing posture)

13. Nature of the participants
Please note that investigations governed by the Code of Practice that involve any of the types of participants listed in B1(b) must be submitted to the University Ethics Committee (UEC) rather than DEC/SEC for approval.

Do any of the participants fall into a category listed in Section B1(b) (participant considerations) applicable in this investigation?: Yes ☐ No ☒
If yes, please detail which category (and submit this application to the UEC):
N/A

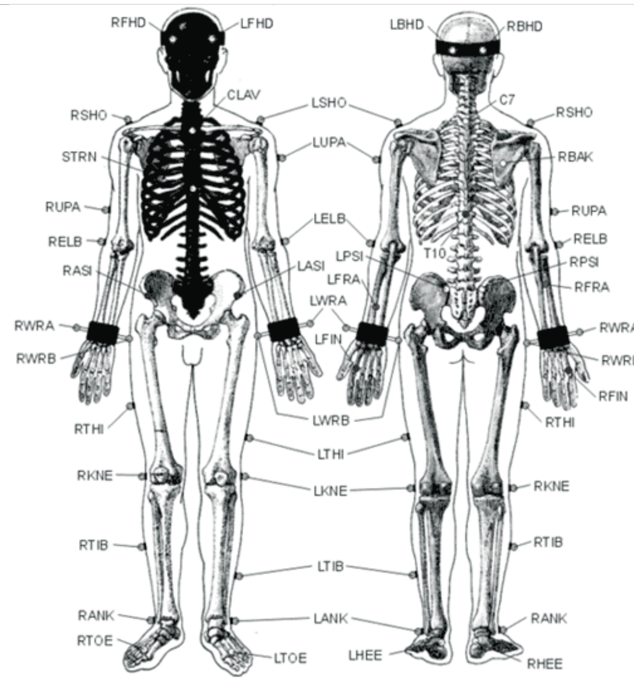
14. Method of recruitment

Describe the method of recruitment (see section B4 of the Code of Practice), providing information on any payments, expenses or other incentives.

An e-mail will be sent round the Biomedical Engineering department asking for volunteers/recruits. There will be no payments to any person involved.

15. Participant consent
Please state the groups from whom consent/assent will be sought (please refer to the Guidance Document). The PIS and Consent Form(s) to be used should be attached to this application form. All participants will be given a consent form to fill in, before being recruited to the study, ensuring that they have read the PIS Form. The PIS and Consent Form is attached in this application form.

16. Methodology
Investigations governed by the Code of Practice which involve any of the types of projects listed in B1(a) must be submitted to the University Ethics Committee rather than DEC/SEC for approval.
Are any of the categories mentioned in the Code of Practice Section B1(a) (project considerations) applicable in this investigation? ☐ Yes ☒ No If 'yes' please detail:
Describe the research methodology and procedure, providing a timeline of activities where possible. Please use plain English. The design methods that will be used, involve the VICON motion capture system to monitor the position of markers attached to the skin and clothes of the subject. First, the body weight, height and some other somatometric characteristics of the subjects will be measured for input to Vicon software. The subject will have to wear tight-fitted clothes and have one's lumbar region, shoulders and upper extremities exposed. The subject will have markers attached with adhesive tape. The markers will be attached as shown in the picture with addition of markers on the pubic symphysis and on the lumbar spine:



The participant will be asked to take up various postures of daily life (standing, sitting, lying supine and on the side, and variations of the lying on the side posture with different angles of flexion, and abduction of the hips, flexion of the knees and torso). The researcher might use a simple goniometer to check for the exact angles of flexion but this will not be taken into consideration in the data analysis, since the markers and Vicon system will provide the information on the exact angles in each joint. This will help reduce time and effort during the investigation. These postures will be replicated three times for some seconds each, and the subject will not need to do anything more than stand/sit/lie in the position instructed. The poses will be easy to follow. In cases that a pose is not achieved as instructed orally and visually, the researcher will position the subject discreetly. Then the position of the markers will be recorded and the data will be used by the researcher for analysis to calculate the orientation of body segments and for statistical analysis.

It is expected that the assessment will be completed within one hour.

What specific techniques will be employed and what exactly is asked of the participants? Please identify any non-validated scale or measure and include any scale and measures charts as an Appendix to this application. Please include questionnaires, interview schedules or any other non-standardised method of data collection as appendices to this application.

The researcher will measure somatometric data of the subject (height, weight, knee and ankle circumference, leg height). The data will be directly inserted in the software. The markers will be attached in specific landmarks on the subject's body, as described in the Plug-in-Gait manual of the Vicon system, for full body measurements, with the addition of a marker on the pubic symphysis and some markers on the lumbar region and spine. Then we will record the position of the markers for 5 seconds each, to obtain static measurements of the position of the markers in 3D space.

Where an independent reviewer is not used, then the UEC, DEC or SEC reserves the right to scrutinise the methodology. Has this methodology been subject to independent scrutiny?
Yes ☐ No ☒
If yes, please provide the name and contact details of the independent reviewer:
N/A

17. Previous experience of the investigator(s) with the procedures involved.
Experience should demonstrate an ability to carry out the proposed research in accordance with the written methodology.

Miss Vlaserou is a postgraduate student in Biomedical Engineering. She has had classes in clinical and sports biomechanics and specialised training to familiarize with the Vicon system. As a Bachelor in Physiotherapy, she has knowledge of anatomy and kinesiology which makes her competent in attaching superficial markers as needed for this project.

Dr. Ewen has many years of experience in movement analysis in clinical and research environments. Most of this experience has been with the Vicon system which will be used in this study. His experience has included research with hip replacement patients. In addition to standard movement analysis of level walking (gait analysis) and analysis of other activities of daily living (e.g. stair use), he has also used movement analysis in none standard situations such as posture analysis and body orientation.

Mr. Clarke and Mr. Deep are both experienced consultant orthopaedic surgeons specialising in hip and knee replacement surgery. Both routinely use navigation techniques during surgery and Mr. Deep has a particular interest in navigation techniques applied to hip replacement surgery.

Dr. Deakin has many years experience in clinical research and has managed many studies with hip replacement patients. She also has a master's degree in Medical Statistics.

18. Data collection, storage and security

How and where are data handled? Please specify whether it will be fully anonymous (i.e. the identity unknown even to the researchers) or pseudo-anonymised (i.e. the raw data is anonymised and given a code name, with the key for code names being stored in a separate location from the raw data) - if neither please justify.

Data recorded will be pseudo-anonymised in a numbered format for the subjects (staring from X for females and Y for males). A separate master file linking a subject to code will be stored securely and accessibly only to the investigators. The raw data files and any processed files will then be stored on our secure server which requires password access. Data will be managed in way compatible with the university's data management policy.
Explain how and where it will be stored, who has access to it, how long it will be stored and whether it will be securely destroyed after use: Data will be initially collected and stored securely on the VICON workstation in the user account of the researchers, requiring a username and a password to access. Data will be stored on investigators hard drive and transported with USB flash drive. Both devices would be password protected to ensure that only investigators would have access to data. Access will be available only to the above named investigators. Data will be kept for 1 year post-investigation, to allow publication of the work in a peer-reviewed journal.
Will anyone other than the named investigators have access to the data? Yes ☐ No ☒ If 'yes' please explain: N/A

19. Potential risks or hazards
Describe the potential risks and hazards associated with the investigation: There is a risk for minor skin irritation by the use of adhesive attachment of markers. To ensure no damage is done by the sticky pads those with poor quality skin will be excluded from the study. There is the risk of the participant feeling uncomfortable during the attachment of markers. Thus, the participation to the research is voluntary and the participants may anytime leave without consequences. The participants will be informed about the sequence of steps throughout the investigation and the researcher will be discreet.
Has a specific Risk Assessment been completed for the research in accordance with the University's Risk Management Framework (Risk Management Framework)? Yes ☒ No ☐ If yes, please attach risk form (S20) to your ethics application. If 'no', please explain why not: N/A

20. What method will you use to communicate the outcomes and any additional relevant details of the study to the participants?

If any information is desired by the participants, they can communicate with the researchers via their university emails, which were provided in the PIS form.

21. How will the outcomes of the study be disseminated (e.g. will you seek to publish the results and, if relevant, how will you protect the identities of your participants in said dissemination)?
The outcomes of the investigation will be published in the MSc thesis of Panagiota Vlaserou. It is intended to publish outcomes of the study at appropriate conferences and, if of an appropriate standard, in a peer reviewed journal.

Checklist	**Enclosed**	**N/A**
Participant Information Sheet(s)	☒	☐
Consent Form(s)	☒	☐
Sample questionnaire(s)	☐	☒
Sample interview format(s)	☐	☒
Sample advertisement(s)	☒	☐
Any other documents (please specify below)		
	☐	☒
	☐	☒
	☐	☒
	☐	☒
	☐	☒

Participant Information Sheet

Name of department:

Biomedical Engineering

Title of the study: Assessment of composite movements between spine, pelvis, hip, knee and ankle in different postures of daily activities in normal persons

Introduction

My name is Panagiota Vlaserou and I am undertaking a postgraduate MSc in Biomedical Engineering at the University of Strathclyde. I am a fully trained physiotherapist who is used to carrying out physical assessments of individuals. Thank you in advance for taking the time to consider helping me with my thesis investigation.

Please read this information and if everything is clear and you are willing to participate, complete the consent form. If you have any questions regarding this study, please do not hesitate to contact myself -the researcher- via e-mail or phone (contact details are at the end of this document).

Background

Total hip arthroplasty is a widely performed surgery with 7609 patients having received primary operation in Scotland in 2013. The main concern of researchers is to find a way to reduce the rate of post-operative complications (dislocations, excessive component wear etc.), which cause revision surgery in approximately 2.6% of the patients in Scotland. The mal-positioning of the cup (pelvic component of the artificial joint) is a major reason for complications. Current thinking amongst orthopaedic surgeons is that the position of the pelvic component may need to be individualized to bring better results.

The amount of pelvic tilt is the orientation of the pelvis as seen from the side. Some people have a tilted pelvis to the front, which make their pubic bones more prominent. By tilting the pelvis, posture of the person and the curvature of the spine temporarily changes, but people tend to have a natural amount of pelvic tilt in standing, which changes in different positions or activities (e.g. while walking). This pelvic tilt is considered to be a factor that can change the required cup position but currently, it is not regularly used in the assessment of the patients undergoing surgery. Research implies that individual pelvic movement needs to be incorporated in the planning of the surgery to bring better results.

The pelvic orientation is also an important factor during the execution of the surgery, as it indicates the position of the pelvis in the operating room and guides the surgeon to the correct placement of the artificial joint.

What is the purpose of this investigation?

In this study, we will use three-dimensional video motion analysis to register the orientation of the pelvis, spine and lower limbs of normal persons in different postures of daily life. We need to find out if there is a specific correlation between the orientation of the pelvis to other body parts, within 3D space, and what the variations are among individuals. There is a lack of knowledge in this specific field, but this study could provide evidence to lead towards a more individualized approach in total hip arthroplasty in the future.

This research is a straight-forward way to provide information that would lead to improvement in this field.

Do you have to take part?

Participant's contribution is voluntary and the participants are free to withdraw from the project at any time, and also withdraw their data from the investigation, without having to give a reason and without any consequences. If you feel uncomfortable at any time during the study you may leave. Participating or not participating in this project will in no way influence your standing or relationship within the University.

What will you do in the project?

You can only participate on completion of the consent form. You will not be paid for you participation in this investigation. The location of the investigation is shown immediately below. If you take part in the study you will be given a time to attend the laboratory for the study. It should take no longer than an hour for you to complete the investigation.

Biomechanics 3

Department of Biomedical Engineering

University of Strathclyde

Wolfson Building

106 Rottenrow

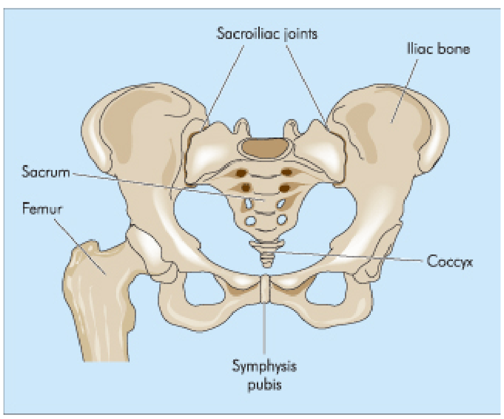
Glasgow

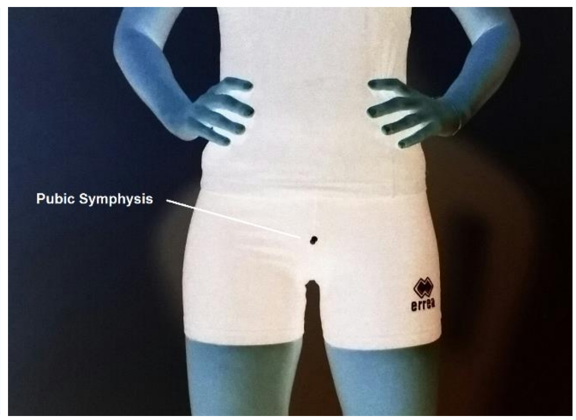
You will be required to attend your allocated time slot at the biomechanics laboratory. You will have some reflective markers attached on your skin and clothes, on various anatomical landmarks, on your trunk, pelvis and lower limbs. Twelve infrared light emitting cameras alongside Vicon software will be used to capture the position of these markers in space and generate a 3-D stick figure. These cameras do not record a video of you, but only the position of the markers. If there appears the need for taking pictures of you, you will be clearly asked for permission. If you do not consent, that will not affect in any way your participation in the research. You should feel free to answer negatively and express any objections during the investigation.

You will need to wear tight-fitted, comfortable clothes, preferably shorts and a sports bra or top. If you do not have this type of clothing it will be provided. Men will be asked to remove their top for the measurements. It is important that your clothes do not move along your skin, as this might interfere with the readings and cause possible errors. The markers will be attached using sticky pads and may cause some minor discomfort on removal.

First,the researcher will need to measure you to get your height, weight, knee width, ankle width, leg length and the distance of your shoulder's center of rotation to the acromion (both located on your shoulder) which will be used as an input to the software.

Then, the markers will be attached on your skin and clothes. Since the current study needs to provide clinically useful information the anterior pelvic plane, which is a reference plane used in surgery, needs to be registered. That means that three bony landmarks of the pelvis will be palpated and matched with a marker. Therefore, we will need to attach a marker on your pubic symphysis (above clothing) which is the bony prominence at the front of your pelvis just above the genitals as shown in the picture below.





Some people might find this embarrassing. If you think you will find this uncomfortable or embarrassing it is best that you do not take part in the study.

Following this, you will be asked to take some comfortable positions in any order; stand in an upright position, lie down supine (on your back) and on your side, sit comfortably on a chair. You will also need to take some positions with the guidance of the researcher, so that positions in the operating room are simulated. That may need the handling of the researcher, so that the pose is achieved.

Once the data of you in all the different positions has been recorded by the infrared cameras no more is required of you.

Why have you been invited to take part?

You have been invited for this investigation because you are an able bodied adult with Body Mass Index (BMI) less than 30. Ideally this investigation would be done with adults near the age of 60 because of its association with total hip replacement surgery. However if you are under 60, you are still needed in this investigation and the value of the results will not be degraded anyway. To participate, you should make sure that you do not have any allergies to adhesive tape, also that you do not suffer from any sort of neurologic/musculoskeletal or other disease. Pregnant women or women who have recently given birth should not participate, because these conditions might temporarily affect posture. Participants should not have a history of orthopaedic surgery and shouldn't have any hearing or visual impairment that would obstruct them from following directions. Finally, it is needed that you be able to stand, sit and lie unassisted.

What are the potential risks to you in taking part?

There is a potential risk that your skin may be aggravated slightly by the use of the adhesive attachment of the markers. If you feel that your skin may be allergic to any forms of adhesive then it is best that you choose not to involve yourself in this investigation.

Also you will be asked to adopt a number of different positions. If you have pain and musculoskeletal/neurological or other health-related syndromes that will prevent you from sitting in a normal height chair, lying on your back or side, then it is best that you choose not to involve yourself in this investigation.

There is also a risk that you might feel uncomfortable or be embarrassed during the placement of the marker on your pubic symphysis. If you think you will find this uncomfortable or embarrassing it is best that you do not take part in the study.

What happens to the information in the project?

Your information will be used as previously stated and all information taken including subject identity will be kept pseudo-anonymized, which means that each subject will be randomly given a code that will represent his/her identity during the whole investigation. There will be a file with participants' data that corresponding to codes. All data will be safely stored for 2 years after the investigation in the university's computers in the Vicon workstation and in the hard-drive and a flash-drive that will be protected by username and password. Only investigators will have access to these files.

The data from the study will be published as an MSc thesis. It may also be published at conferences or as a journal paper. You will be referred to only as subject X in any literature associated with the investigation, so it will be entirely confidential. If any images taken of you are used this will be edited to ensure that you cannot be identified from them.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

Thank you for reading this information – please ask any questions if you are unsure about what is written here.

What happens next?

If you are happy with everything that has been stated above and are still willing to be involved in this investigation, please e-mail us to say you are willing to consent and you will be allocated with an investigation time slot that would be convenient to you (reply to panagiota.vlaserou.2014@uni.strath.ac.uk or jon.clarke@strath.ac.uk). You will need to sign the Consent Form to Research prior participating, so a copy will be provided to you in the beginning of your time slot, or you can return the one you will find attached at the end of this document.

If you are unwilling for any reason to be involved in the investigation, this is completely understandable and I thank you for your attention.

If you require any feedback on your data or on the outcome of the investigation then don't hesitate to contact me the researcher.

This investigation was granted ethical approval by the Departmental Ethics Committee of Biomedical Engineering at the University of Strathclyde.

If you have any questions/concerns, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Linda Gilmour

Secretary to the Departmental Ethics Committee

Department of Biomedical Engineering

Wolfson Centre, 106 Rottenrow

Glasgow G4 0NW

Tel: 0141 548 3298 E-mail: linda-gilmour@strath.ac.uk

Researcher Contact Details:

Panagiota Vlaserou

MSc student - Biomedical Engineering

Physiotherapist

E-mail: panagiota.vlaserou.2014@uni.strath.ac.uk

Telephone: 0752 606 5507

Chief Investigator Details:

Mr Jon Clarke, PhD FRCS Glasg(Tr&Orth)

Clinical Lecturer

E-mail: jon.clarke@strath.ac.uk

Telephone: 0141 548 303

Consent Form

University of Strathclyde Glasgow

Name of department: Biomedical Engineering

Title of study: Assessment of composite movements between spine, pelvis, hip, knee and ankle in different postures of daily activities in normal persons

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences.
- I understand that participating or not participating in this study will in no way influence my standing or relationship within the University.
- I understand that I can withdraw my data from the study at any time.
- I understand that any information recorded in the investigation will remain anonymous and no information that identifies me will be made publicly available.
- I consent to being a participant in the project
- I consent to images being taken as part of the project **Yes/ No**

I (PRINT NAME)	Hereby agree to take part in the above project
Signature of Participant:	Date

MATLAB SCRIPT

```
function GiotaMagicWand

File=[];Path=[];

[File,Path,~] = uigetfile( ...
   {'*.c3d','c3d file(s) (*.c3d)'}, ...
   'Select gait file(s) to be reported','Multiselect','off');

file = btkReadAcquisition(File);
markers = btkGetMarkers(file)
noOfFrames = btkGetPointFrameNumber(file)

newFileName = strcat('new',File)

subjectName = input('Subject Name: ', 's');
supine = input('Include LPSI and RPSI?(y/n): ', 's');

LAPP = strcat(subjectName,':LAPP');
RAPP = strcat(subjectName,':RAPP');
PAPP = strcat(subjectName,':PAPP');
LPSI = strcat(subjectName,':LPSI');
RPSI = strcat(subjectName,':RPSI');

Wand1Markers = markers.WAND1;
Wand2Markers = markers.WAND2;
```

```
LAPPframe = input('LAPP frame: ');
RAPPframe = input('RAPP frame: ');
PAPPframe = input('PAPP frame: ');

Wand1LAPP = Wand1Markers(LAPPframe,:);
Wand2LAPP = Wand2Markers(LAPPframe,:);

Wand1RAPP = Wand1Markers(RAPPframe,:);
Wand2RAPP = Wand2Markers(RAPPframe,:);

Wand1PAPP = Wand1Markers(PAPPframe,:);
Wand2PAPP = Wand2Markers(PAPPframe,:);


LAPPpoints = [Wand2LAPP - (525/295.77)*(Wand2LAPP-Wand1LAPP)]
LAPPmat = ones(noOfFrames, 1)*LAPPpoints;
btkAppendPoint(file, 'marker', LAPP, LAPPmat );

RAPPpoints = [Wand2RAPP - (525/295.77)*(Wand2RAPP-Wand1RAPP)]
RAPPmat = ones(noOfFrames, 1)*RAPPpoints;
btkAppendPoint(file, 'marker', RAPP, RAPPmat )

PAPPpoints = [Wand2PAPP - (525/295.77)*(Wand2PAPP-Wand1PAPP)]
PAPPmat = ones(noOfFrames, 1)*PAPPpoints;
btkAppendPoint(file, 'marker', PAPP, PAPPmat );

if supine == 'y'
```

```
    LPSIframe = input('LPSI frame: ');

    RPSIframe = input('RPSI frame: ');

    Wand1LPSI = Wand1Markers(LPSIframe,:);
    Wand2LPSI = Wand2Markers(LPSIframe,:);

    Wand1RPSI = Wand1Markers(RPSIframe,:);
    Wand2RPSI = Wand2Markers(RPSIframe,:);

    LPSIpoints = [Wand2LPSI - (525/295.77)*(Wand2LPSI-Wand1LPSI)]
    LPSImat = ones(noOfFrames, 1)*LPSIpoints;
    btkAppendPoint(file, 'marker', LPSI, LPSImat );

    RPSIpoints = [Wand2RPSI - (525/295.77)*(Wand2RPSI-Wand1RPSI)]
    RPSImat = ones(noOfFrames, 1)*RPSIpoints;
    btkAppendPoint(file, 'marker', RPSI, RPSImat );

end

btkWriteAcquisition(file, newFileName);
```