EVALUATION OF A FLEXIBLE GONIOMETER WITH A VIEW TO DEVELOPING A HIP DISLOCATION ARTICULATION ALERT SYSTEM

SCOTT FRAME, BSc (Hons)

A project submitted in partial fulfillment of the requirements for the degree of Master of Science in Bioengineering

BIOENGINEERING UNIT

UNIVERSITY OF STRATHCLYDE

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DECLARATION

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ABSTRACT

Hip dislocation is a common complication following hip arthroplasty surgery. In an attempt to reduce the risk of hip dislocation patients would be provided with physiotherapy advice, positioning aids in bed, elevated toilet seats and also a hip orthosis. Current designs of hip orthoses attempt to block excessive flexion and adduction, however, compliance and correct positioning of the orthosis on the patient is often poor.

The objective of this study was to evaluate a biaxial flexible goniometer and assess its suitability for potential integration into a hip articulation electronic warning alert system. The initial trials involved bench calibration and validation of the flexible goniometer to evaluate its accuracy when measuring a known angle on the jig. A second calibration and validation was trialled on three subjects to compare the hip angles measured by the Vicon® motion analysis system with those of the flexible goniometer.

With angles in one plane only (flexion-extension or abduction-adduction) the cross-talk was of the order of 2%. However, when combining larger angles of flexion-extension and abduction-adduction the cross-talk increased to 8%. In addition, there were significant errors induced in hip angle measurements of both the flexible goniometer and Vicon system due to soft tissue deformation when fitted to a subject. In conclusion, the errors developed during subject use produced insufficiently accurate hip angle measurements to support the use of this sensor in a hip articulation alert system.

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Chapter 1: INTRODUCTION

1.1. Aims

The hip joint of a post hip arthroplasty patient is exposed to increased risk of dislocation due to a number of factors (Woo et al, 1982). Current management is based upon restricting articulations which increase the risk of dislocation; flexion (>90°), adduction (>5°) and internal rotation (Peak et al, 2005). Several braces are available which attempt to block movement into unstable alignments of the hip joint. There are many disadvantages associated with this style of brace, and with that in mind, this study set out to examine the suitability of a biaxial flexible goniometer (Biometrics Ltd, Newport, Gwent, UK, Model SG150) in the measurement of hip position with potential for integration into a hip articulation alert system.

Flexible goniometers have been frequently used in the study of hand and knee joint motion (Jonsson and Johnson, 2001; Myles et al, 2002). Whilst the hand and knee joint studies examined measured biaxial movement, only articulation in one plane was anatomically predominant. The flexible goniometer used in this study is being recommended by the manufacturer (Biometrics Ltd, Newport, Gwent, UK) for use in the measurement of biarticular hip motion. However, actually validating its use in vivo at the hip joint has not been studied, to the author's knowledge. The aim of this study is two-fold; validate the flexible goniometer's accuracy in a bench test, followed by on-subject testing to evaluate its accuracy in vivo.

1.2. Approach

At the beginning of the study several joint angle measurement sensors were investigated to decide which would be most suitable for the application of a hip articulation alert system. The sensors reviewed included manual goniometers, triaxial potentiometers, flexible goniometers, gyroscopes and accelerometers. A comparison identified the flexible goniometer as potentially being the most suitable for this application.

The initial objective of this study was to evaluate the flexible goniometer during bench testing. An alignment jig was designed and manufactured in order to accurately position the end blocks of the flexible goniometer to simulate flexion, extension, abduction and adduction. Of particular interest was the effect of combined movements which had previously been shown by Rowe et al (2001) to produce cross-talks.

Whilst bench alignment testing was suitable for analysis of the flexible goniometer in a controlled environment, the proposed use for the device was to measure hip joint alignment in human subjects. In fitting the device to a subject it was hypothesised that there would be errors induced in the measured angles due to soft tissue deformation. On-subject testing would involve Vicon® system hip angle measurements being compared with the flexible goniometer angle measurements.

1.3. Structure of Thesis

This thesis consists of eight chapters. Chapters two, three and four discuss the background deemed pertinent to this thesis.

Chapter two reviews the issues associated with hip dislocation which includes a discussion of hip arthroplasty, dislocation risk factors and management of the dislocated hip. Chapter three summarises the anatomy of the hip joint, discussing the components of its physiology which help to maintain hip joint stability. Chapter four reviews the flexible goniometer and Vicon system which were used during the experimental procedures.

Chapter five discusses the methodology employed which includes the equipment used, set-up, and both calibration and validation protocol.

Chapter six presents the results recorded during the experiments, while chapter seven discusses these results as well as other issues related to the work done. Finally, chapter eight includes a brief conclusion of the body of work performed throughout this study and contains suggestions for future work.

Chapter 2:
HIP DISLOCATION

2.1. Introduction

During 2007-2008 the National Joint Registry (www.njrcentre.org.uk) recorded a total of 73,632 hip arthroplasty procedures in England and Wales. The total consisted of 66,839 primary arthroplasties, 6,757 revised arthroplasties and 284 re-operations (without prosthesis replacement). This represented a two-fold increase from the annual number of recorded hip arthroplasties since 2003-2004 (figure 2-1).

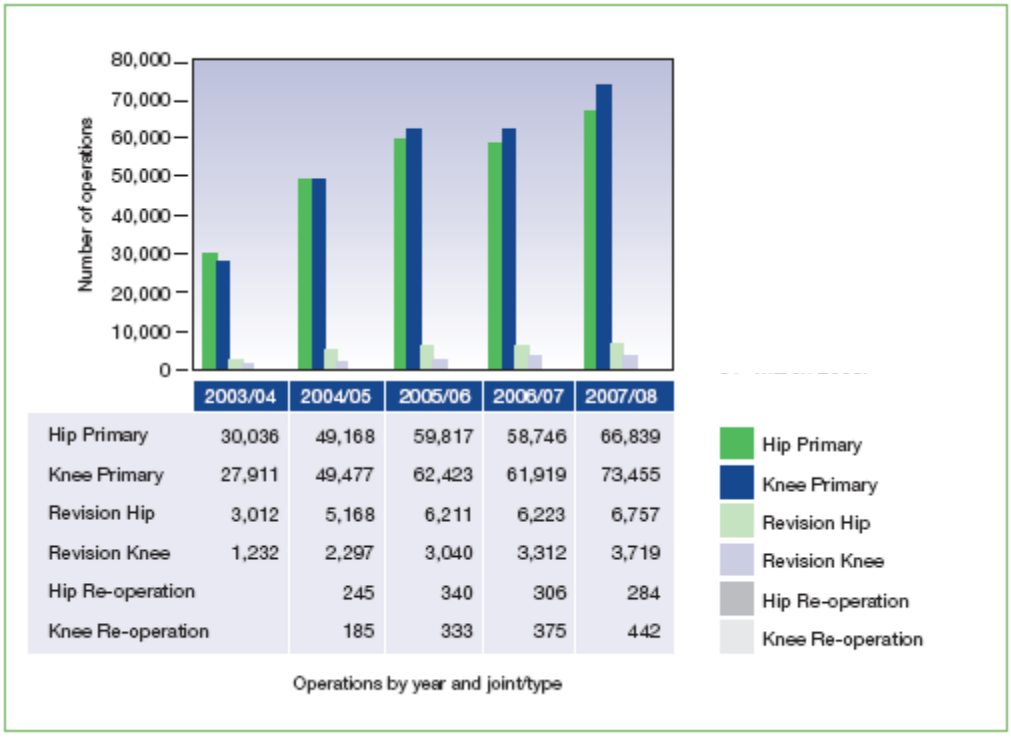


Figure 2-1: Joint replacement operations entered on the NJR 1st April 2003 – 31st March 2008 (modified from www.njrcentre.org.uk.).

A number of researchers have examined the rates of dislocation of hip arthroplasty patients, which in part, emphasises the magnitude which hip dislocation poses in hip replacement surgery. Key studies by Woo et al (1982), Morrey et al (1992) and Phillips et al (2003), to name only a few have highlighted and identified the significance and non-significance of the many variables associated with hip arthroplasty surgery. A recent study by Conroy et al (2008) reported hip dislocation to affect between 1-5% of primary total hip arthroplasty patients and 7-10% of revision arthroplasty patients. The management of dislocation in the cohort of primary arthroplasty patients was with closed reduction (surgery not required) in approximately two-thirds of cases according to Kristiansen et al (1985) and Garcia-Cembrelo et al (1992). This supports the finding of Krushell et al (1991), Dorr et al (1983) and Morrey et al (1992) who identified 13- 45% of their cohort requiring surgical intervention.

The research shows that the majority of hip dislocations are managed conservatively which may highlight the potential for an articulation alert system to be integrated into the care of patients at a high risk of dislocation.

2.2. Dislocation Risk Factors

The increased risk factors to dislocation included patient factors, design of hip prostheses, surgical technique, and post surgical rehabilitation protocol. There have been several papers published in this area, and continue to be published, as hip dislocation remains a significant complication of hip arthroplasty despite technical advances.

The first study to comprehensively examine the numerous risk factors associated with total hip arthroplasty was by Woo et al (1982). The study investigated whether there were any correlations between each variable and the rate of dislocation. Woo carried out a retrospective study of 10,500 total hip arthroplasty patients from 1968 to 1978. The number of dislocations recorded by the cohort was 331 which corresponded to a dislocation rate of 3.2%. In order to ease analysis of the data, the variables were classified into three groups; preoperative, perioperative and postoperative, as shown in table 2-1.

Preoperative	Perioperative	Postoperative
Age	Surgical approach and size of femoral head	Time to dislocation
Sex	Range of motion	Direction of dislocation
Side of operation	Myofascial tension	Reoperation
Previous history of hip surgery	Orientation of the acetabular cup	
Preoperative diagnosis	Trochanteric migration	

Table 2-1: Categorisation of the variables associated with hip dislocation following a primary hip arthroplasty. The variables highlighted in red indicate a variable which significantly increased the rate of dislocation. (adapted from Woo et al, 2001)

The three variables which were identified as carrying the greatest risk of hip dislocation were preoperative diagnosis and trochanteric migration. The preoperative diagnoses which resulted in the highest rates of dislocation included those with prostheses instability (loosening), previous extensive soft tissue trauma (e.g. girdlestone procedure) and previous resectioning of bone (e.g. failed previous arthroplasty). The rates of dislocation in the fore mentioned indications were 25.7%, 13.6% and 13.0% respectively. In the case of trochanteric migration, where the greater trochanter of the femur had been relocated to improve the efficiency of the abductor muscles, 194 hips had experienced non-union and there was sufficient space that it had been recorded. A significant proportion of these hips were unstable (17.5%), representing a six-fold increase in dislocation compared to the united-trochanteric group. The biomechanical rationale which would explain this correlation is the deactivation of the hip abductors which insert into the greater trochanter and play an important role in hip stabilisation.

Alberton et al (2002) carried out a similar study to that of Woo et al (1981), however, this time examining a cohort (n=1548) of hip revision patients. As perhaps expected, there were a higher proportion of dislocations (7.4%) than may have been expected in a primary arthroplasty cohort. The results identified significant risk factors in trochanteric migration and smaller femoral head sizes. However, in contrast to Woo et al (1981), sex, surgical approach and direction of dislocation were not found to significantly influence the rates of dislocation. Further to this, a reduction in dislocation was identified with the use of an elevated rim liner which, due to a

deepening of the prosthetic acetabulum, reduced the risk of dislocation to less than twice than those without.

The development of prosthetic components, surgical techniques and improved biomedical research has resulted in improved hip arthroplasty success. Regardless of these developments hip dislocation remains a major complication due to the complex biomechanics of the hip joint.

2.3. Post Hip Arthroplasty Management

The rehabilitation programme for hip arthroplasty patients is generally initiated as soon as possible following surgery (24 - 48 hours), unless complications exist. Physiotherapists are primarily the professionals responsible for returning the patient back to a safe ambulatory status whilst ensuring a maximum level of rehabilitation is achieved. The use of hip braces may also be used as part of a post surgical rehabilitation programme, in particular when patients are deemed by the surgeon or physiotherapist to be at a high risk level of dislocation.

2.3.1. Physiotherapy Management

The first stage of management involves the review of the medical notes to obtain any post-operative instructions and/or medical status. Ensuring the patient is ready to begin rehabilitation an assessment of respiratory function and lower limb function is carried out. The patient would then be mobilised

up into walking by the physiotherapist and assistant, using a frame or elbow crutches whilst observing hip safety precautions to avoid dislocation. During periods of non-ambulation exercises for the buttocks, quadriceps, hip flexors and foot exercises should be followed to improve normal limb muscle function and facilitate circulation. When the patient is deemed safe they can initially mobilise three times a day, walking to the toilet for example. Advice would be provided on safe articulation of the hip joint to reduce the risk of dislocation. The articulations which must be avoided are excessive flexion (> 90°), adduction (no more than that involved in the patient's normal gait) and internal rotation (not exceeding normal comfortable position in stance/gait). Advice which would typically be given to patients would include:

- Do not stand on the affected leg and rotate
- Avoid cross-legged sitting
- Avoid sudden flexion of the hip – do not sit down too quickly
- Do not exceed 90° of hip flexion – do not sit in low chairs, kneel or crouch

Six weeks following surgery rehabilitation should have reached a stage of good gait, reasonable muscle power and be able to do most functional activities. When the patient returns to normal activities it is imperative the patient follows the precautionary advice for several months to a year.

2.3.2. Hip Dislocation Braces

Hip spicas have been used in the management of hip instability for many years. In todays clinical environment they are more commonly witnessed in the treatment of congenital hip dysplasia cases (figure 2-2) where immobilisation and an abducted alignment of the femur is required to obtain hip stability. A more functional series of braces have been developed which are more adjustable and can be used during ambulation.



Figure 2-2: A plaster of paris hip spica used in the management of congenital hip dysplasia. (www.aafp.org – 07/08/2009)

Popular hip abduction braces used in the U.K. include the Hiptric® (figure 2-3), manufactured by Ossur (Ossur Head Office, Grjothals 5, 110 Reykjavik, Iceland), and the Newport 4® (figure 2-4), manufactured by OrthoAmerica (6333 N. Orange Blossom Trail, Suite 220, Orlando, FL 32810). The concept of these braces is that the range of motion can be setup to prevent movement into an unsafe hip position, or, simply hold the hip in an increased abduction alignment for bed use. Patient compliance with abduction braces is often poor due to issues with discomfort, bulkiness and

excessive restriction imposed during rehabilitation. Possibly a greater design issue relates to poor suspension which could result in incorrect alignment of the joint centre. The incongruent alignment of the brace joint centre axis relative to the anatomical axis must result in a shearing load being applied around the pelvis and thigh component of the hip brace. This must be a negative design aspect considering the patient will most commonly be in the acute stages of post surgical healing.



Figure 2-4: The Hiptric® (Ossur Head Office, Grjothals 5, 110 Reykjavik, Iceland)



Figure 2-3: The Newport 4® (OrthoAmerica, 6333 N. Orange Blossom Trail, Suite 220, Orlando, FL 32810).

Dewal et al (2004) studied the rates of dislocation in two groups of patients; first-time dislocation (n=91) and recurrent dislocations (n=58). The first-time and recurrent dislocation groups were reviewed at a mean of 4 years and 3.7 years respectively. Sixty-one percent of first-time dislocation and sixty –four percent of the recurrent dislocation patients presented with at least one further dislocation after using an abduction brace. There was therefore no significant evidence identifying abduction braces as a solution to hip dislocation. The author concluded abduction bracing following a closed reduction is ineffective at preventing hip re-dislocation.

Chapter 3:
HIP JOINT ANATOMY

3.1. Introduction

This section summarises the structure and function of the various components which constitute the hip joint. Of particular interest are the features of its construction which enable the hip joint to remain stable throughout large ranges of motion as well as transmitting high forces and moments.

3.2. Hip Overview

The hip joint, also known as the coxofemoral joint, is the articulation between the femoral head and the acetabulum of the pelvis. The physiological shape of the hip joint can be described as a ‘ball and socket’ enabling movement in three planes; flexion/extension in the sagittal, abduction/adduction in the coronal and medial/lateral rotation in the transverse. Whilst large ranges of movements are elicited at the hip joint the primary function of the hip joint is to support the load applied by the head, arms and trunk during closed chain loading. However, it must still be capable of maintaining stability and function during open chain activities, most commonly swing phase during gait. Of the two, the hip is better equipped to cope with closed chain

activities, according to Levangie et al (2005). The loads experienced during closed chain activities are high, and as such, the design plays a crucial role in ensuring the hip joint remains stable throughout the full range of motion (ROM). The primary components which contribute to good hip joint construction include the boney structure, joint capsule and ligaments, and musculature.

3.3. Boney Structure

3.3.1. The Acetabular Labrum

The proximal component of the hip joint is the cup-shaped acetabulum, which is located on the lateral aspect of the pelvis. An important component of the acetabulum in terms of providing hip stability is the acetabular labrum. The labrum covers the entire circumference of the acetabular rim deepening the socket, increasing its concavity through its triangular shape, and grasps the femoral head to maintain contact with the acetabulum (figure 3-1). It also functions to provide increased proprioception and pain sensation; the proprioceptive response improves hip control whilst the pain sensation improves protection of the acetabular rim when excessive loads are applied.

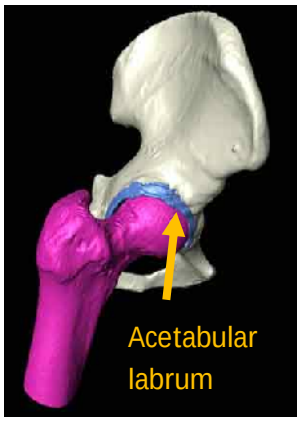


Figure 3-1: The labrum provides additional femoral head coverage increasing hip stability (www.hipkneeclinic.co.uk – 07/08/2009)

3.3.2. Alignment of the Acetabulum

The alignment of the acetabulum is known to influence the function and stability of the hip joint. One method of quantifiably measuring the alignment of the acetabulum is to use the centre edge (CE) angle method, as shown in figure 3-2. This is used to measure the inferior tilt angle of the acetabulum relative to pelvic alignment. Anda et al (1986) found the average CE angle of the acetabulum to be 38° and 35° in men and women respectively.

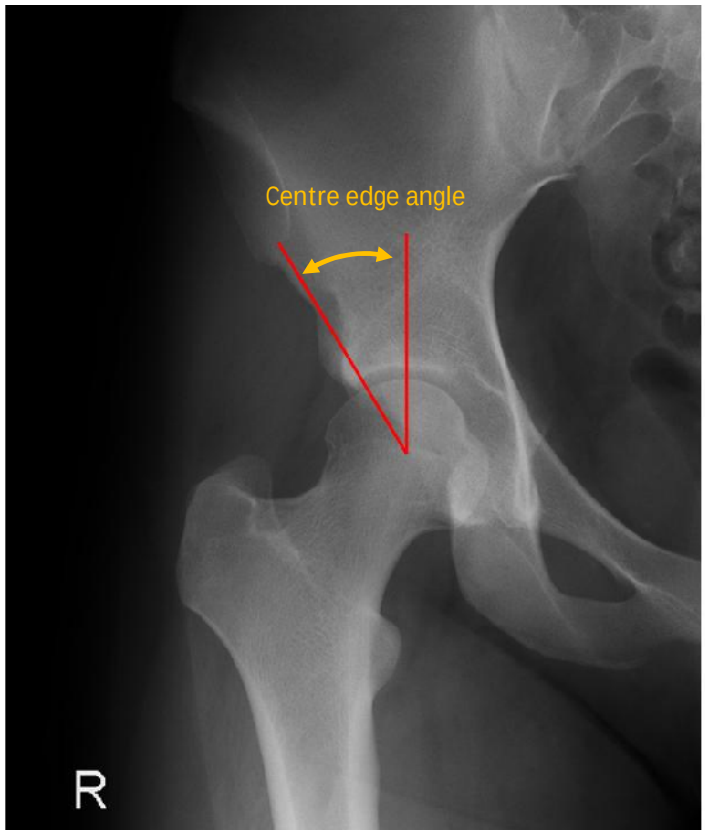


Figure 3-2: The centre edge angle is measured by measuring the angle between a vertical line through the centre of the femoral head and a line from the centre of the femoral head to the edge of the acetabulum. (www.orthopaedia.com)

The acetabulum is also slightly anteriorly tilted; Anda et al (1986) reporting the average angle of acetabular anteversion to be 18.5° and 21.5° in men and women respectively. However, a study by Kapandji et al (1987) reported significantly higher values of up to 30°- 40°. Pathologic increases in this angle are associated with decreased joint stability and increased risk of anterior dislocation of the head of the femur.

3.3.3. Hip Position

In a position of neutral stance there is increased exposure of the femoral head both anteriorly and superiorly. This is of particular interest in the case of acute post arthroplasty patients, where there is potential for soft tissue weakness around the femoral head due to surgical trauma. The increased exposure of the femoral head may give rise to the idea that the femoral head is at greater risk of dislocating from the acetabular cup (see figure 3-3).

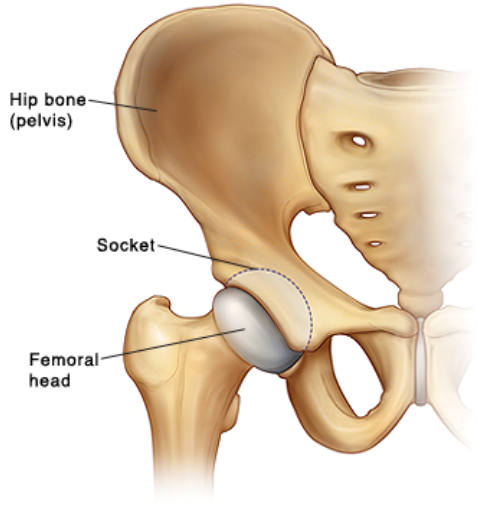


Figure 3-3: In a neutral position during stance the femoral head is exposed anteriorly and to a lesser extent superiorly. (www.mountnittany.org-20/07/2009)

Kapandji et al (1987) reports increased stability and reduced exposure of the femoral head can be achieved during non-weight bearing by flexion, abduction and slight lateral rotation of the femur relative to the pelvis. This alignment is commonly termed the “frog-legged” position.

3.3.4. Loading Effects

Weight-bearing results in the acetabulum elastically deforming to increase the contact area with the femoral head. Whilst the femoral head alignment increases surface contact with the acetabulum superiorly, anteriorly and posteriorly. The non-articular acetabular fossa creates a partial vacuum improving femoral head and acetabular contact further. Wingstrand et al (1990) concluded that the vacuum created plays a stronger role in stabilisation than any of the capsuloligamentous structures.

3.3.5. The Joint Capsule

The joint capsule has been cited as a significant factor in increasing joint stability by Williams (1999) and Stuart et al (2002).The capsule is an irregular structure constructed of dense fibres orientated both longitudinally and obliquely where there are three regions constituting the capsular ligaments. The capsule is additionally thick anteriosuperiorly at the location of the most significant stresses, and is much thinner in the posteroinferior aspect where the boney acetabulum protects the capsule from the higher loads. The capsule itself is attached proximally around the entire periphery of the acetabulum, beyond the labrum. Distally it is attached to the base of the femoral neck, proximal to the greater and lesser trochanter. The femoral head is therefore completely encapsulated by the capsule.

3.4. Ligaments

3.4.1. Ligamentum Teres

Ligamentum teres is the intra-articular ligament between the acetabular notch and the fovea of the femoral head. The ligament experiences tension when the hip is placed in semiflexion and adduction. However, Foss et al (1991) found that it did not play such an important role in joint stabilisation, rather, a conduit for the blood supply of the obturator artery and the nerves which supply the femoral head.

3.4.2. The Anterior and Posterior Ligaments

The hip joint capsule consists of three ligaments; two anterior ligaments and one posterior. The anterior ligaments are the iliofemoral and pubofemoral ligaments which align to form a Z-shape on the anterior aspect of the joint capsule (figure 3-4). The posterior ligament is the ischiofemoral ligament which originates from the acetabular rim and the acetabular labrum and inserts into the inner surface of the greater trochanter. The majority of the fibres are spirally orientated around the femoral neck and are blended with those of the capsule, whilst a small proportion are more horizontally orientated.

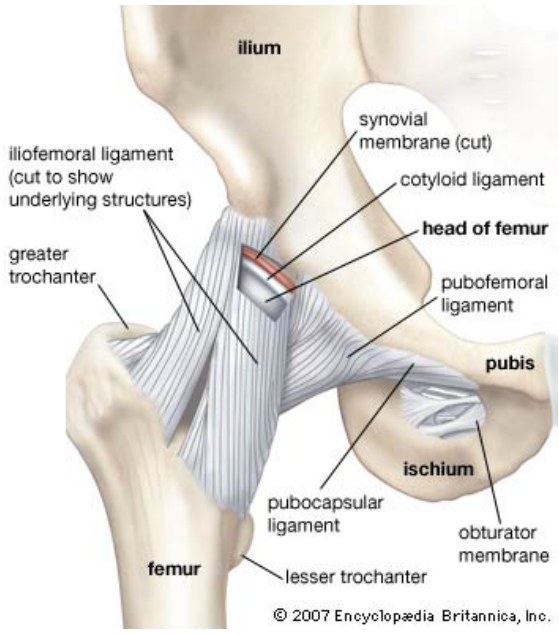


Figure 3-4: The Z arrangement of the iliofemoral and pubofemoral ligaments on the anterior aspect of the hip joint capsule. (www.britannica.com- 07/08/2009)

3.4.3. Loading of the Ligaments

A study by Foss et al (1991) examined the loading action of the ligaments surrounding the hip during loading. They concluded that moments applied in each of the three axis of the hip induced loading in at least one of the joint ligaments and that the forces applied through the ligament were dependent upon the alignment of the femur relative to the acetabulum. A consensus was reached that both the capsule and ligaments tightened with full hip extension. The anterior ligaments are reported to be stronger than the posterior ligaments, being able to withstanding greater loading. Overall, the capsule and ligaments are very strong, preventing distraction even under strong traction forces.

In normal stance the centre of gravity of the head, trunk and arms falls posteriorly to the hip joint, creating a hip extension moment. The excessive hip joint extension moment induces tension in the capsule and anterior ligaments which maintains hip joint stability. The strength of the capsule and ligaments is such that they alone, without any muscle control, can support standing as long as the centre of gravity line passes posterior to the hip joint.

The hip joint is regarded as being in a closed packed position when it is aligned in extension with slight abduction and internal rotation [Williams, 1999]. As hip extension increases the ligaments twisting around the femoral neck and head draw the head into the acetabulum. However, interestingly, when the hip joint is in the closed packed position and most stable, the joint does not have the greatest congruency. As previously mentioned optimal congruency is achieved in a flexed, abducted and laterally rotated position. Kapandji et al (1987) reported the hip of a healthy subject to be least stable and more vulnerable to dislocation in a flexed and adducted alignment. A large force which is applied up the femoral shaft in the direction of the hip is likely to result in hip dislocation. This is commonly seen in accident and emergency departments where subjects involved in car accidents receive impact to the knee from the dashboard.

3.5. Musculature

Hip joint musculature is regarded as being complex in its actions as varying hip alignment can change the functional ability and action of several muscles. For example at 0° hip flexion the piriformis muscle is a lateral rotator but at 90° hip flexion it is a medial rotator.

The following section attempts to highlight the stability features which each muscle group applies in its action and function. The main muscle groups are the flexors, extensors, adductors, abductors and the medial and lateral rotators.

3.5.1. The Hip Flexors

The primary function of the hip flexors is to bring the swinging leg forward during gait. They are also required during closed chain activity in order to resist strong hip extension moments which may be developed when the body passes over the weight bearing foot.

The hip flexors consist of nine muscles with action lines crossing the anterior aspect of the hip joint. The primary hip flexors are the iliopsoas, rectus femoris, tensor fascia lata (TFL) and sartorius. The iliopsoas is regarded as the most important as it is almost solely responsible for flexing the hip from a 90° sitting position, or beyond. The action of the iliopsoas is such that there is very little medial or lateral rotation applied during hip flexion activity.

3.5.2. The Adductors

The adductor muscle group includes the pectineus, adductor brevis, adductor longus, adductor magnus and the gracilis muscle. All the adductors, excluding gracilis, originate from the inferior ramus of the pubis and insert along the line of the linea aspera of the femur. Gracilis, however, originates from the pubic symphysis and pubic arch and inserts into the medial shaft of the tibia, making it a biarticular muscle. All the muscles are anteriomedially aligned, therefore resulting in a hip adduction moment.

Janda et al (1965) concluded that the main function of the hip adductors was to stabilise the pelvis rather than actively move the hips during open chain activity. The adductors are therefore synergists to the abductors in order to create pelvic stability.

3.5.3. The Extensors

The primary hip extensors are the gluteus maximus muscle and the hamstring muscle group. The gluteus maximus is the largest of the lower extremity muscles and tends to be most active when the load applied exceeds body weight. Compared to the hamstrings the gluteus maximus has the largest muscle action which is greatest when in neutral hip alignment.

The muscles which make up the hamstrings are the long head of biceps femoris, semitendinosus and semimembranosus. The hamstrings originate from the ischial tuberosity and insert into the fibular head and proximal tibia, making them a biarticular muscle group which control hip extension and knee flexion. The muscle action of this group increases as with hip flexion up to 35° and decreases thereafter.

3.5.4. The Abductors

The abductors consist predominantly of gluteus medius and gluteus minimus for active abduction. The muscles act together to either abduct the femur in open chain or stabilise the pelvis during closed chain loading; particularly during unilateral stance. Jensen et al (1971) and Olsen et al (1972) report the abductors as optimally functional in a neutral or slightly adducted position. Levangie et al (2005) describes the gluteus minimus as having a tendinous insertion into the joint capsule as it passes to the greater trochanter. The function of this insertion is to retract the capsule during hip abduction to prevent entrapment and tighten the capsule to stabilise the femoral head in the acetabulum.

3.5.5 The Lateral Rotators

Lateral rotation at the hip is controlled by six short muscles. They are the obturator internus and externus, the gemellus superior and inferior, the quadratus femoris, and the piriformis muscles. The posterior fibres of the gluteus medius, minimus and maximus also contribute along with the primary actions of these muscles. The alignment of the primary lateral rotators is perpendicular to the orientation of the shaft; ideal for applying a lateral rotation action. These muscles are also effective joint compressors due to the combined action orientation of the muscles relative to the head and neck of the femur. Delp et al (1999) states that the majority of the lateral rotators muscle action is reduced with increased flexion, apart from the obturator externus and quadratus femoris. In general, the compressive forces are applied throughout the full range of hip joint motion, despite the reduced lateral rotation function with increased flexion.

3.5.6. The Medial Rotators

Medial rotation of the hip joint occurs as a secondary action of selected muscles, with no muscles having medial rotation as their primary function. The muscles which contribute to medial rotation are the anterior portion of the gluteus medius, gluteus minimus, and the tensor fascia lata muscles. Basmajian et al (1985) also identify the adductors as medial rotators of the hip with the exception of gracilis. Whilst Arnold et al (2001) documents an increase in strength of medial rotation torque with an increased hip flexion angle.

3.6. Range of Motion

Passive joint motion ranges have been cited by Norkin et al (2003). Hip flexion with the knee extended was 90° and with the knee flexed 120° (relaxing hamstring tension). Hip extension ranged from 10° to 30°. If the knee is flexed during extension this may limit movement further due to rectus femoris muscle tension. Hip abduction is 45° to 50°; range can be limited by gracilis muscle tension (adductors). Adduction range is less with only 20° to 30° normally achieved; this is limited by the tensor fascia lata (TFL) and its associated iliotibial band. Rotation was measured with the hip flexed to 90° and the results concluded 42° to 50° could be achieved.

The ROM required for normal gait is 30° flexion, 10° hyperextension, 5° of both abduction and adduction and 5° of both medial and lateral rotation.

Chapter 4:
FLEXIBLE GONIOMETERS AND DIGITAL 3D MOTION CAPTURE

4.1. Introduction

A goniometer is defined as a device which can measure angles. There are several different methods of measuring an angle with a goniometer, although different types of goniometers will suit different applications. In terms of human motion analysis, goniometers can measure local joint angles when attached across two or more joint segments with the output enabling quantitative clinical evaluation or experimentation.

Three of the most commonly used electrogoniometers have embedded circuitry, they include potentiometers, fibre optics and strain gauges to obtain angular deviations. The greatest advantage of electrogoniometers over manual goniometers is that they can measure in both spatial and temporal domains producing a continuous angle output with respect to time. Electrogoniometers have been found to be popular form of motion capture due to their simplicity, high sample rate and affordability (Legnani et al, 2000; Myles et al, 2002).

4.2. Flexible Goniometers

The most commonly used flexible goniometers are based upon strain gauge or fibre optic technology, however, for the purpose of this study we are only examining the strain gauge type. Both have the advantage of having a variable centre and do not require a specific centre of rotation centre in order to calculate any given angle. This is a great advantage over conventional manual goniometers which required accurate identification of the joint centre. This is very useful when dealing with anatomical joints, such as the hip, where locating the exact joint centre beneath the soft tissue can be difficult. The end-blocks of the device are fixed proximal and distal to the joint centre so that the relative deflection of the strain gauge wire measures a variable output voltage.

4.3. Mechanical Properties of the Strain Gauged Electrogoniometer

The biaxial flexible goniometer used throughout this study was a Biometrics SG150 biaxial flexible goniometer (Biometrics Ltd, Newport, Gwent, UK). The goniometer consisted of a base element which was a symmetrically circular spring steel base wire, approximately 0.3mm, gauged with four circular constantin signal wires, each aligned 90° apart and allowed bending about any axis (figure 4-1). Each pair of diametrically opposed resistive elements formed a calibrated half-bridge strain gauge transducer (Jonsson and Johnson, 2001). The orientation of one pair of elements measured

flexion/extension, whilst the perpendicular aligned pair measured abduction/adduction.

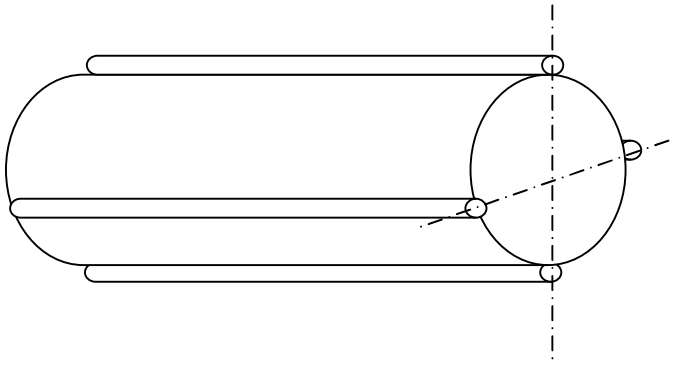


Figure 4-1: The principle design of the strain gauge biaxial flexible goniometer. The strain gauge elements equally distanced 90° apart to create two half-bride strain gauge transducers.

The Biometrics SG150 models had blocks at the proximal and distal ends of the goniometer to allow attachment to a subject, as shown in figure 4-2. The strain gauged elements were contained within a lightweight spring to protect the elements from physical damage. The distal block had an internal spring which was designed to allow linear translational movement of up to 35mm; allowing for translational movements when a joint articulates.



Figure 4-2: The biaxial flexible goniometer. (Biometrics Ltd, Newport, Gwent, UK. Model: SG150)

Several studies (Legnani et al, 2002; Myles et al, 2002; Rowe et al, 2001) have attempted to ascertain the accuracy and repeatability of the electrogoniometers. A series of controlled tests were used to investigate the measurement properties of the flexible goniometers.

Legnani et al (2002) examined the effects of torsion throughout a range of proximal and distal block orientations, finding the degree of error to increase with increasing torsion and increasing flexion/extension alignment. When the electrogoniometer was flexed to 90° and rotated 30° the degree of error ranged from 1° to 3°. A maximum error was noted when the electrogoniometer was flexed/extended to 90° and a 90° rotation was applied producing an error of approximately 2° to 10°.

Rowe examined the difference between and within electrogoniometers. Six different goniometers were calibrated in the morning and repeated again in the afternoon. The calibration coefficients for the morning calibration vs. the afternoon calibration were then compared using the best-fit lines; an error of only 0.3% was recorded. When comparing the electrogoniometers to each other the error ranged from -1° to +2°. This would indicate there are some small discrepancies involved in the manufacture of these devices. It therefore may be beneficial to precalibrate each sensor individually before use. In general, the flexible goniometer was reported to be stable, precise, accurate and repeatable in performance.

4.4. Digital Three-Dimensional Motion Capture

Sutherland attributes the first TV/motion analysis systems to E. H. Furnée based at the Faculty of Applied Physics, Technical University, Delft, Netherlands in 1967. Paper discs which were highly reflective in ultraviolet light were used to measure the joint angles of a cat walking on a treadmill where the ultraviolet light was pulsed, so as to prevent “smearing”. Using a marker system, where the dimensions of the marker were known allowed calculation of a scaling factor. The factor could then be used to transform the digitized pixel units into a global reference coordinate. When the position of three markers was known kinematic measurements such as joint alignment could be calculated. Whilst this form of motion capturing was suitable for two dimensional analysis, the rotation of a joint outside the axis of the camera induced errors (Areblad et al, 1990). The development of a three dimensional analysis system was therefore necessary to accurately calculate joint movements which occurred outside the camera axis.

The evolution of computers, with increased processing speeds and data handling capabilities, supported the development of more complex digital three dimensional optical motion analysis systems. The faster and more capable of which were even able to process the data whilst it was being recorded. A key component in the semi-automatic digitisation of digital raw video was the use of circle fitting algorithms. The algorithms were designed to detect the reflective circular shapes, which were in high contrast to the surrounding area. The cameras were mounted with strobe lights which ran parallel to the camera lens axis, each camera capable of detecting the reflective circular image provided the line of sight was not blocked. On

visualisation and identification of the reflective circle an x, y coordinate could be calculated for the global reference system. Vicon® (Video CONvertor) is a very powerful gait analysis tool which is used in many research facilities to obtain accurate gait results. The most recent Vicon system has infrared light emitting diodes incorporated into the camera unit, enabling filtration of environmental artefacts produced by ambient lighting. The multiple positions of the synchronised cameras make it possible to calculate and quantify the position of the markers in three dimensions. The global reference system, around which these coordinates are based, is constructed by calibrating the camera positions in the laboratory. When two or more cameras identify the markers, with the circle fit algorithm, the vector rays pass through the centroid and intersect, or almost intersect, allowing a three dimensional coordinate to be calculated which best solves this intersection. The Vicon system has a high degree of accuracy and 3D coordinate analysis, which explains why this system is used in many biomechanical studies.

The use of 3D optical motion camera systems are regarded as the premier human kinematics motion analysis system. As with all motion analysis systems, however, there are also several limitations in the use of a three dimensional motion analysis system. The main limitations include cost, need for direct line of sight of the markers, restricted capture area, reduced resolution at greater distances from the cameras, and skin motion and tissue deformation errors.

The cost of a 3D camera system can be very high and is greatly influenced by the need for several cameras. As human motion studies often involve arms

and legs swinging during activities, markers can easily be occluded from view of the cameras. Therefore, multiple cameras need to be positioned to enable visualisation throughout the data collection period, in particular where whole body capturing is required.

The cameras are all calibrated to examine an area within their field of view. Therefore, analysis of the markers is limited to a predetermined volume. If the field of view is increased to improve the 3D capture volume then the resolution of the captured markers reduces as the marker reflections occupy a smaller proportion of the image sensor. The accuracy of the circle fitting algorithm is dependent upon the number of pixels recorded for each marker, hence, fewer pixels results in a less accurate circle.

The placement of the reflective markers is also very important when attempting to assess human motion kinematics of joints. Capozzo et al (1996) found the marker placed over the greater trochanter to become linearly displaced in the anterio-posterior direction by 30mm when the hip was flexed to 60°. Medio-lateral movements resulted in a motion artifact of within 15mm whilst external rotation causes a relative posteroanterior direction of 30mm when the hip is rotated 45°. During walking the marker moves anterior and superior during the first two-thirds of the swing phase whilst it moves posterior and inferior for the remainder of the gait cycle. The results obtained when skin motion artifacts are an issue affects the usability of the results obtained.

Chapter 5: METHODOLOGY

5.1. Methodology Overview

The aims of the project were to investigate by means of both bench and subject testing the suitability of a biaxial flexible goniometer (Biometrics Ltd, Gwent, UK, Model SG150) in the measurement of biaxial hip alignment. This section describes the bench and subject trials undertaken.

5.2. Flexible Goniometer Bench Test Equipment

The equipment used in the bench calibration and validation was a strain gauge amplifier, a custom-made jig and an AVO meter.

The strain gauge amplifier was used as both the voltage supply for the goniometer channels and the amplifier for the output. The strain gauge amplifier was used to complete a half bridge on each channel of the goniometer; channel 1 and 2 measuring flexion/extension and abduction/adduction respectively. The output was amplified by a gain of 200 and the offset could be fine tuned to set the output to zero. The output of each channel was measured using a standard digital AVO meter. Both the bridge voltage and output voltage could be measured independently by switching between channels on the strain gauge amplifier.

5.2.1. The Jig

A simple bench testing jig was designed and manufactured to simulate flexion, extension, abduction and adduction of a hip joint.

The jig, as shown in figure 5-1, consisted of a wooden base plate, two Perspex rotational arms (one for flexion/extension and the other for abduction/adduction), a fixed Perspex block, and finally a wooden stop with Perspex housing. A circular protractor was used to clearly mark the flexion/extension angles on the base plate, in degrees. For ease of visualisation the jig can be viewed as a right hip joint where the fixed Perspex block represents the pelvis and the rotational arms the femur.

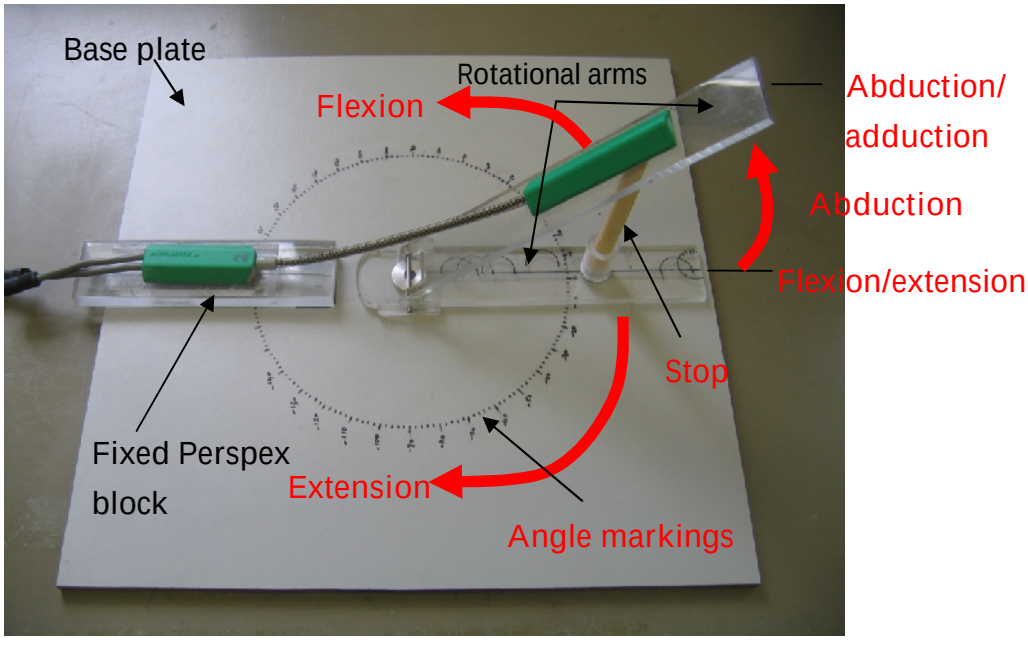


Figure 5-1: Position 1 - The jig components and setup which enabled flexion, extension and abduction to be simulated.

The abduction/adduction arm was only capable of measuring either abduction or adduction due to the base plate causing an obstruction. When the flexible goniometer was aligned as pictured in figure 5-1, only flexion, extension and abduction could be simulated. As adduction also had to be measured the flexible goniometer was rotated 180° on its longitudinal axis so that instead of measuring abduction it measured adduction (figure 5-2). By rotating the flexible goniometer the flexion/extension directions were subsequently reversed.

Due to the distal block of the flexible goniometer being a triangular shape a wooden adapter was made to allow horizontal attachment of the distal flexible goniometer block to the Perspex arm. To compensate for the discrepancy in height an additional Perspex layer was added to the proximal Perspex block to prevent additional errors.

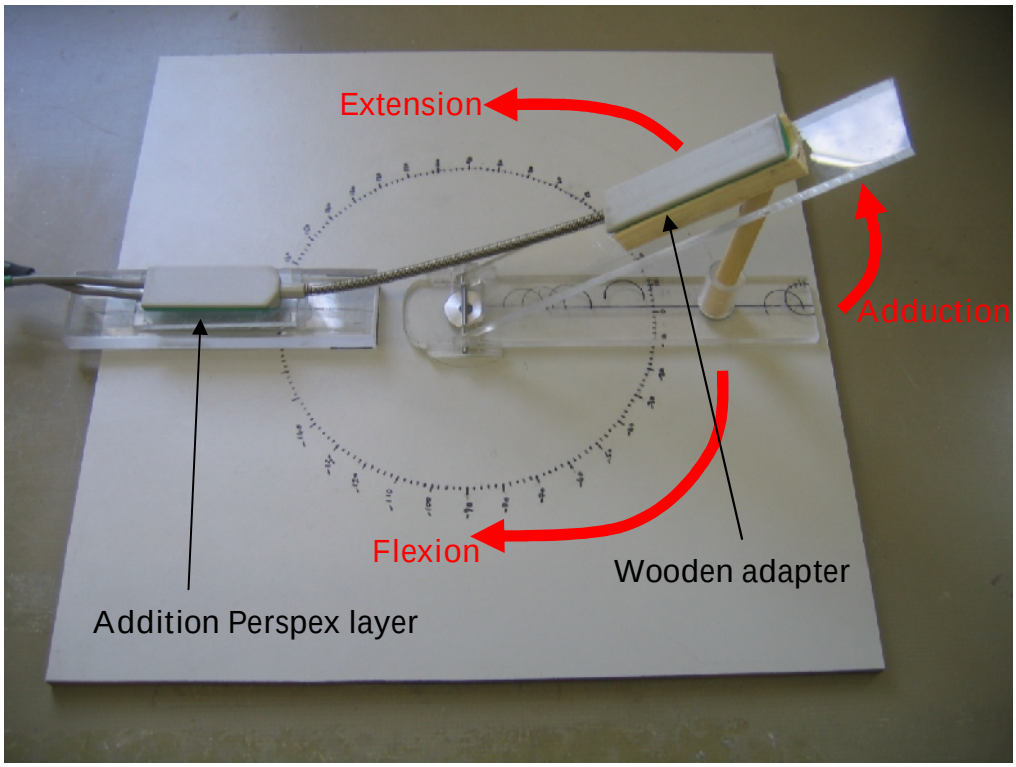


Figure 5-2: Position 2 – Capable of simulating flexion, extension and adduction. A wooden adapter is used to attach the distal block of the flexible goniometer whilst an additional Perspex layer corrects the induced height discrepancy.

5.3. Flexible Goniometer Bench Calibration

Calibration of the flexible goniometer was required to convert the output voltage of each channel into angles of flexion/extension and abduction/adduction, in degrees.

The flexible goniometer was fitted to the calibration jig as shown in figure 5-1. The rotation arms were set into neutral flexion/extension and abduction/adduction and the offset was set to zero in both channels.

To calibrate the flexion/extension axis the rotational arm of the jig was articulated through a range of 40° extension to 120° flexion whilst being set at 0° abduction/adduction throughout. The output voltages were manually recorded at 10° increments, using the AVO meter, in both channel one and two. The rotational arm was articulated through approximately 90° in-between each reading being taken to ensure there was no previous bias affecting the output. The test was repeated three times for each alignment.

The abduction and adduction calibration, as previously mentioned, was complicated by the fact that the flexible goniometer would have to be removed and rotated 180° in order to measure both abduction and adduction. To reduce errors induced by changing the position of the flexible goniometer blocks, the end blocks positions were marked and realigned in the same position following rotation. The range of articulation measured was 50° abduction to 50° adduction whilst maintaining 0° flexion/extension. The angle of the abduction/adduction arm was measured using a protractor and during testing the position was maintained with a wooden stop. The stop position was marked at each 10° increment so the angles could be repeated for the whole series. The test was repeated three times for each alignment.

5.4. Flexible Goniometer Bench Validation

To validate the accuracy of the flexible goniometers a series of tests involving combined movements were required.

The flexible goniometer was positioned in 20° increments of flexion/extension, from 40° extension to 100° flexion, and then abducted through 50° followed by adduction through 50°, in 10° increments. At each position the output voltage was measured using the AVO meter. In between tests the flexible goniometer was, again, articulated through 90° to remove any biases. The tests were repeated three times.

5.4.1. Bench Validation Data Analysis

The amplified output voltage for each of the two channels was recorded in milli Volts. To convert the output voltage into the respective flexion/extension and abduction/adduction angle, the following equation was used:

$\theta = C^{-1}S$; where θ is the angle in degrees, C^{-1} is the inverted calibration matrix and S is the amplified output voltage (milli Volts) from the amplifier.

The results were then plotted on a scatter graph, using Microsoft Excel®, showing the output voltage (milli Volts) of both channels against the jig angle (degrees) during the combined articulations.

5.5. Subject Calibration and Validation Equipment

Subject testing involved comparison of the flexible goniometer output with the kinematic measurements of the Vicon system. Whilst the calibration factors initially obtained from the bench calibration were intended for use in subject validation, they were found to be insufficiently accurate. Therefore, it was necessary to re-calibrate the flexible goniometer on the subject prior to any validation testing.

The same flexible goniometer and amplifier settings as used during static testing were also used for dynamic testing, however, the amplified output was connected to a 16-bit analogue-digital converter, instead of the AVO meter, which was run through the Vicon system. The flexible goniometer was fitted to the subjects left hip using a pair of lycra shorts and Velcro attachments as shown in figure 5-3. Connection cables which ran from the strain gauge amplifier were taped to the subject's torso to prevent additional errors due to movement during activity. The sample rate of the flexible goniometer was set at 120Hz to match that of the Vicon camera system, which enabled direct comparison of the outputs.

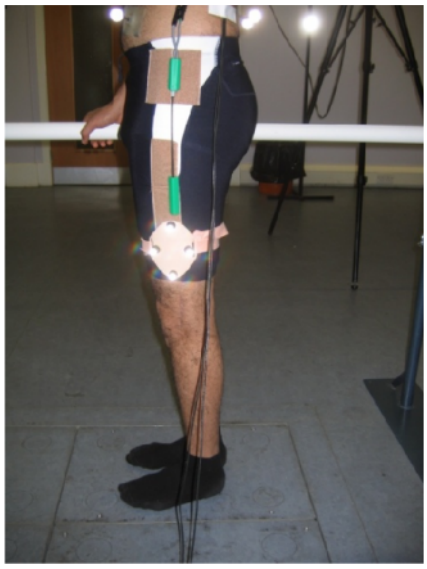


Figure 5-3: Alignment of the flexible goniometer and markers during subject calibration and validation testing.

Data was collected using an eight camera Vicon system with the cameras positioned relatively close to the subject to obtain a higher resolution. The assessment volume could be made relatively small as only standing and sitting tasks were to be assessed. A number of small unobtrusive retro reflective markers were attached to the subject to enable motion joint motion capture. The markers fitted were 4 individual marker attached directly to the subjects waist with double sided tape and a cluster of 4 markers attached to straps which were attached to the lateral thigh of the left leg as shown in figures 5-4 to 5-6.



Figure 5-4: Posterior waist markers

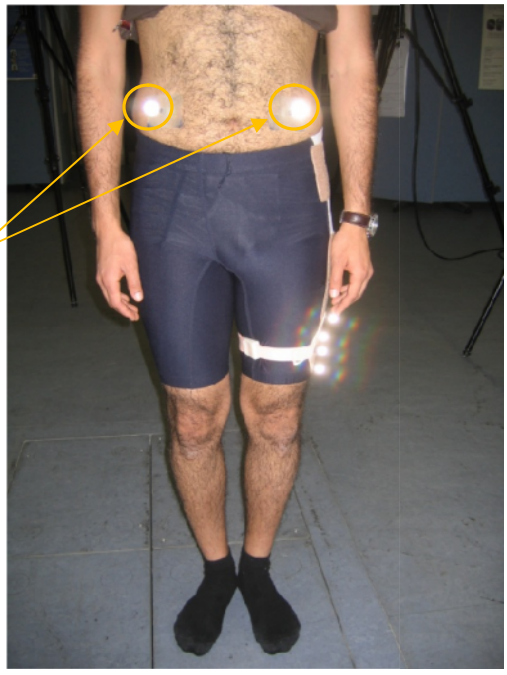


Figure 5-5: Anterior waist markers

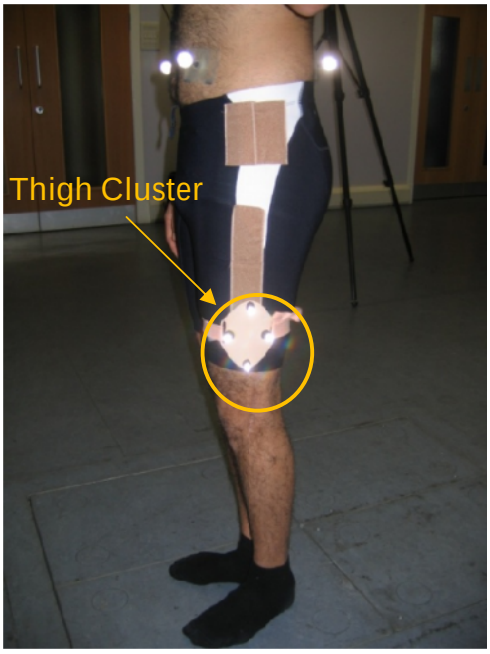


Figure 5-6: The thigh cluster was positioned laterally to enable easier visualisation of the markers without obstruction to the line of sight of the cameras.

5.6. Flexible Goniometer Calibration on a Subject

All the tests were conducted in the Biomechanics laboratory of the Bioengineering Unit, University of Strathclyde. The Vicon system underwent both static and dynamic calibration prior to testing the subjects, ensuring the system accurately obtained the marker positions. Calibration involved the subjects undertaking three hip articulation maneuvers whilst fitted with the flexible goniometer and the reflective markers. A pair of lycra shorts with Velcro panels were provided which enabled attachment of the flexible goniometer to the subjects left hip. The calibration articulations which the subjects were instructed to follow were:

1. Flexion - Subjects performed a flexion movement of the hip joint starting from a neutral alignment and flexing up to in excess of 90°.
2. Extension – The subjects were requested to perform an extension starting from a neutral alignment. The range available would normally only elicit approximately 10° - 15°. The knee was maintained in full extension throughout.
3. Abduction – The subjects were advised to abduct the lower leg with the knee extended and the foot remaining anteriorly aligned, preventing internal/external rotational effects. The range achieved from a neutral alignment was typically in the range of 40°-50°.

   N.B. Subjects were advised to attempt pure plane articulations as only principal axis must be used for calibration.

Each of the calibration articulations was repeated three times.

5.7. Flexible Goniometer Validation on a Subject

To validate the accuracy of the flexible goniometer following calibration, subjects were requested to undertake two adduction activities which would typically increase the risk of hip dislocation in a post hip arthroplasty patient.

The first was a simple standing adduction trial where the subject had to adduct the measured leg in front of the contralateral limb, as shown in figure 5-7. The subject started the trial with the hip in approximately 15° of flexion and simply adducted the hip to a comfortable maximum and then returned back to the original starting position.



Figure 5-7: The standing adduction trial - the subject adducts the hip to a comfortable maximum, starting from a 15° flexed position to prevent contact with the supporting limb.

The second trial was a more complex sitting trial. The trial involved the patient starting in a neutral standing position, flexing the hips to approximately 90° to sit in the chair, adducting the measured hip to sit cross-legged, and then reversing the process to return to neutral standing. Figure 5-8 below shows the cross-legged position achieved during the sitting trial.



Figure 5-8: The (adducted) cross-legged position achieved during the sitting trial.

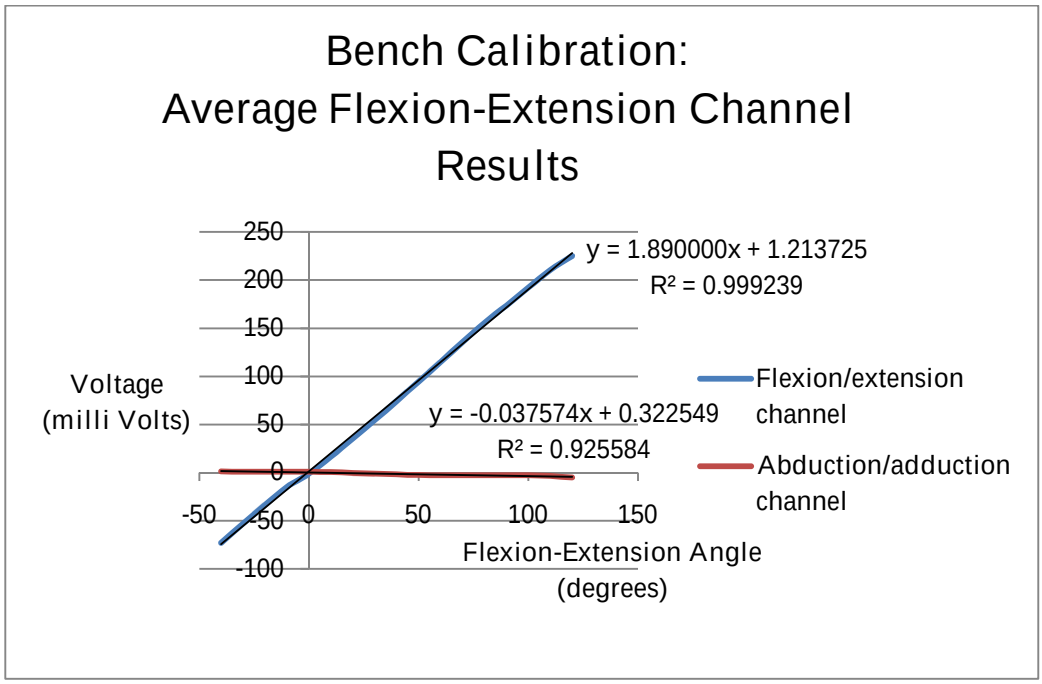
Chapter 6:
RESULTS

6.1. Bench Calibration Results

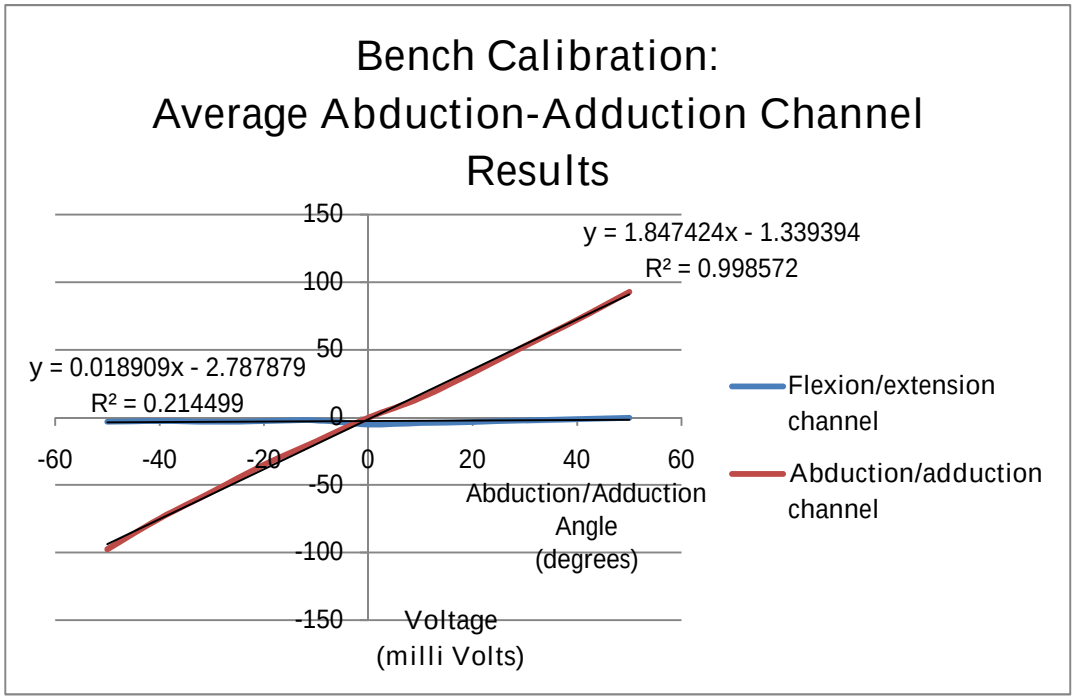
The sign convention used throughout the results section was:

- '+' bias represents the flexion and abduction angle
- '-' bias represents the extension and adduction angle

The average calibration results for the flexion-extension and abduction-adduction channels of the flexible goniometer are shown in graphs 6-1 and 6-2 respectively. Please note the results have been inverted due to the bench calibration simulating a right hip whilst the subject calibration was carried out on a left hip. For the purposes of the discussion, having the bias of the bench and on-subject results the same enabled easier comparison of the results.



Graph 6-1: The average calibration results obtained when articulating the flexible goniometer from 40° extension to 120° flexion whilst being maintained in 0° abduction.



Graph 6-2: The average calibration results obtained when articulating the flexible goniometer from 50° abduction to 50° adduction whilst maintained in 0° flexion.

The linear equation describing the best-fit line for each channel represented the calibration factor (CF) and offset during bench calibration. The calibration matrix (C) and user matrix are shown in table 6-1 and 6-2 respectively.

$$\begin{bmatrix} S_{Flex/Ext} \\ S_{Abd/Add} \end{bmatrix} = \begin{bmatrix} 1.89 & -0.03757 \\ 0.0189 & 1.8474 \end{bmatrix} * \begin{bmatrix} \theta_{Flex/Ext} \\ \theta_{Abd/Add} \end{bmatrix} \text{ (milli Volts)}$$

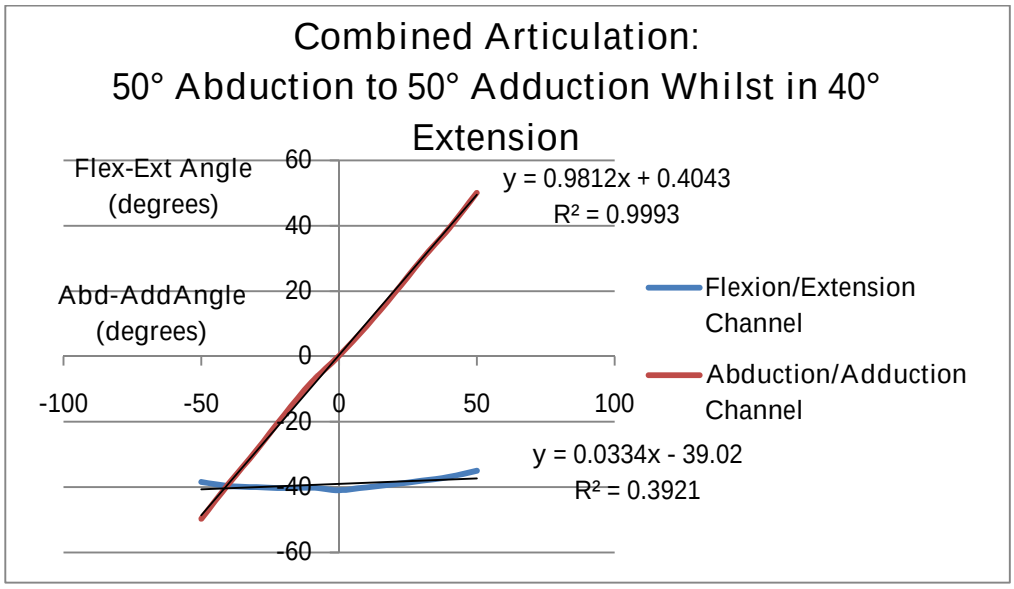
Table 6-1: The bench calibration matrix (C)

$$\begin{bmatrix} \theta_{Flex/Ext} \\ \theta_{Abd/Add} \end{bmatrix} = \begin{bmatrix} 0.529 & 0.011 \\ -0.005 & 0.541 \end{bmatrix}^{-1} * \begin{bmatrix} S_{Flex/Ext} \\ S_{Abd/Add} \end{bmatrix} \text{ (degrees)}$$

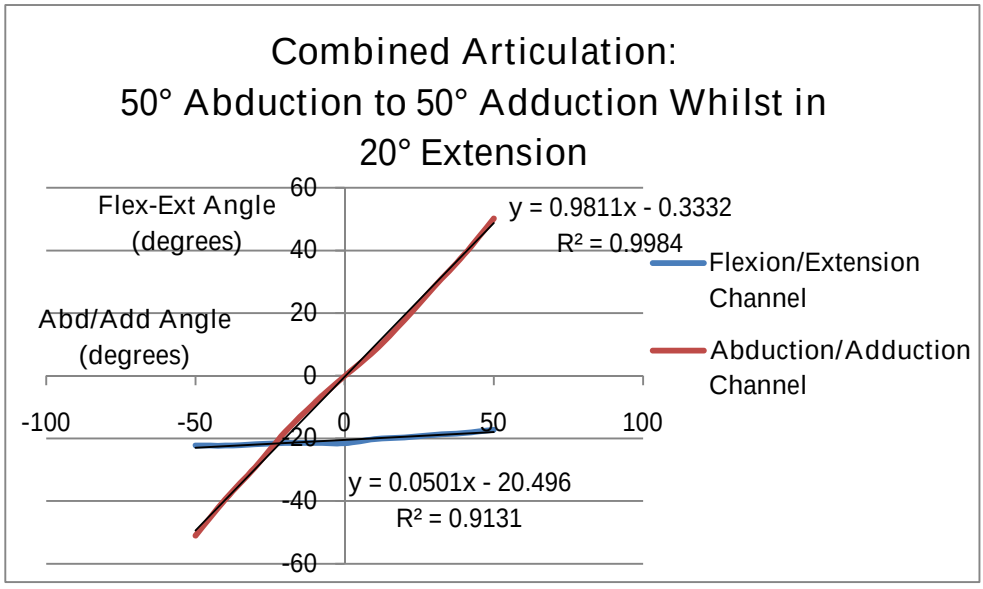
Table 6-2: The user matrix (C^{-1})

6.2. Bench Validation Results

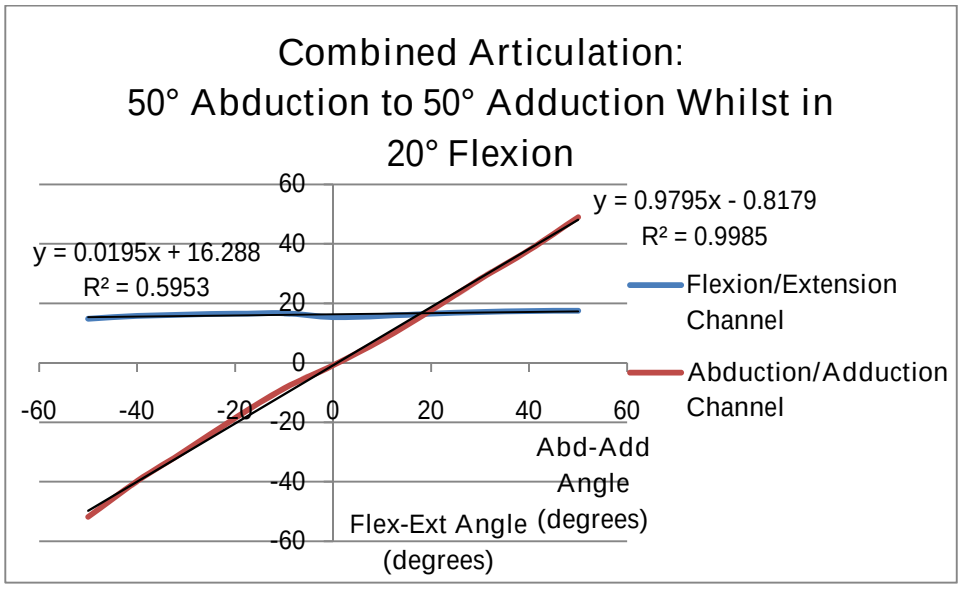
The user matrix was applied to convert the output voltage of each goniometer channel into the positional angle, in degrees. The test was repeated three times for each position and the average results were plotted, as shown in graphs 6-3 to 6-9.



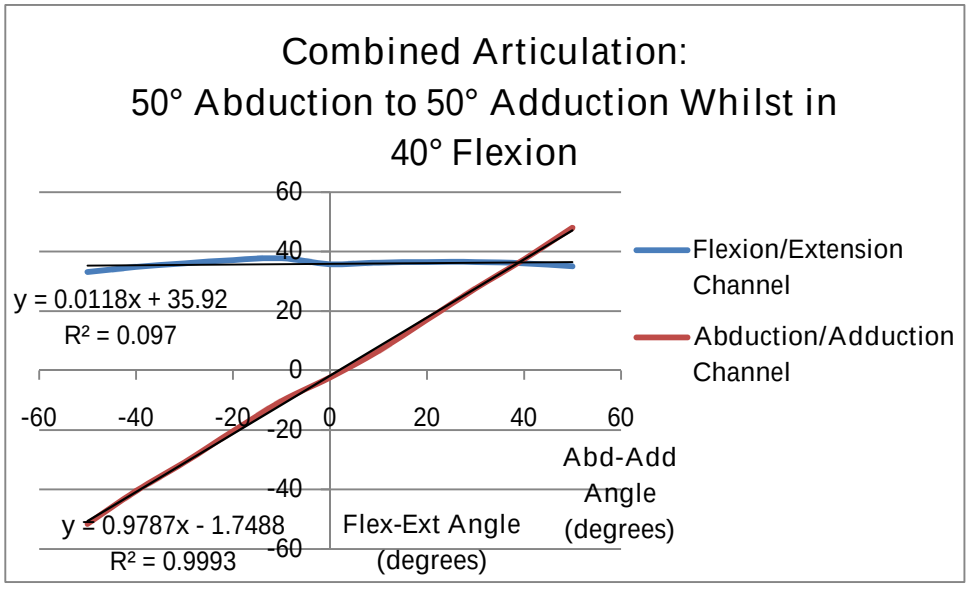
Graph 6-3: The flexible goniometer was articulated from 50° abduction through to 50° adduction whilst aligned in 40° extension.



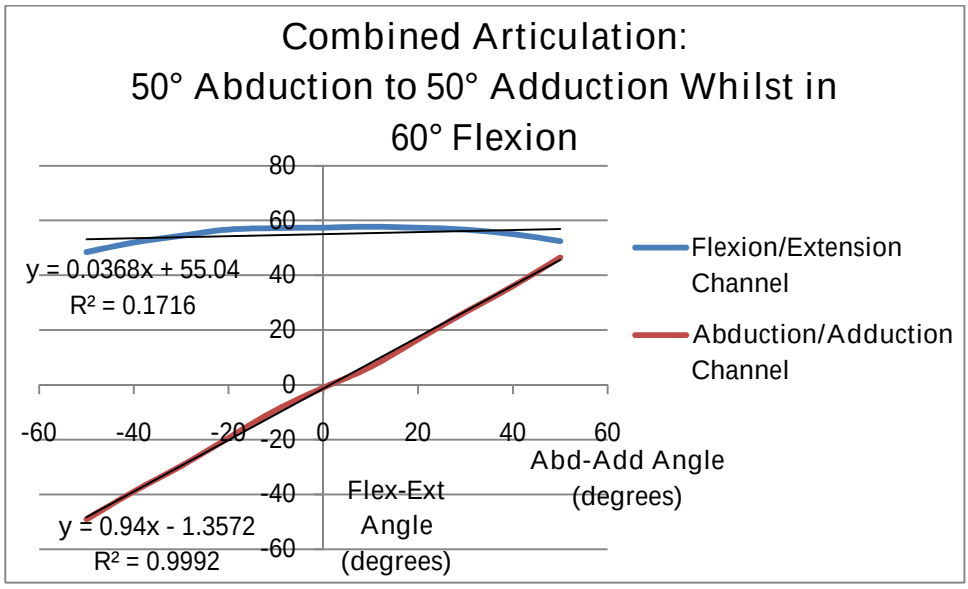
Graph 6-4: The flexible goniometer was articulated from 50° abduction through to 50° adduction whilst aligned in 20° extension.



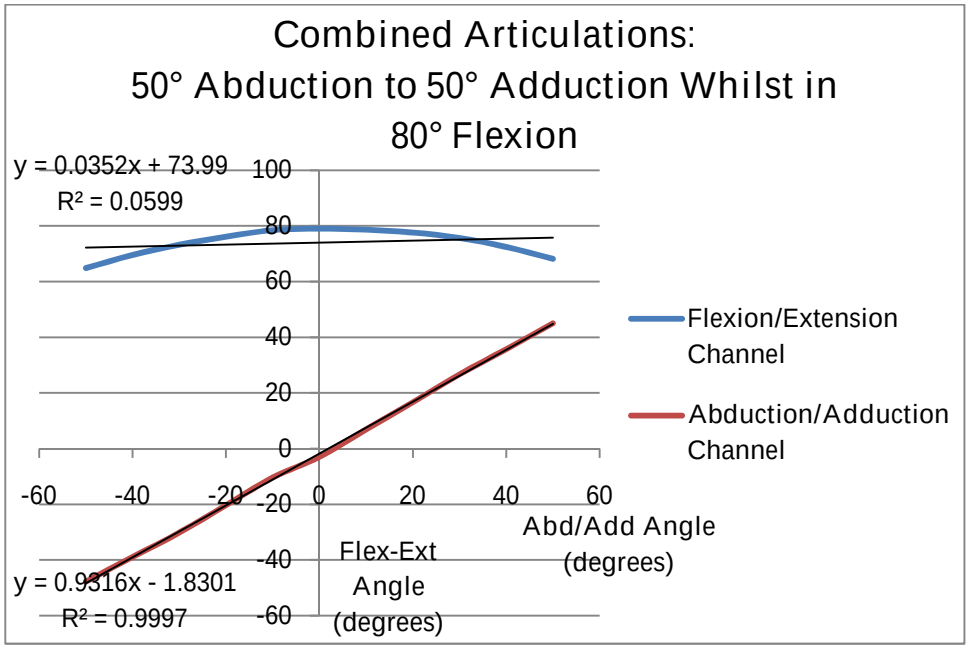
Graph 6-5: The flexible goniometer was articulated from 50° abduction through to 50° adduction whilst aligned in 20° flexion.



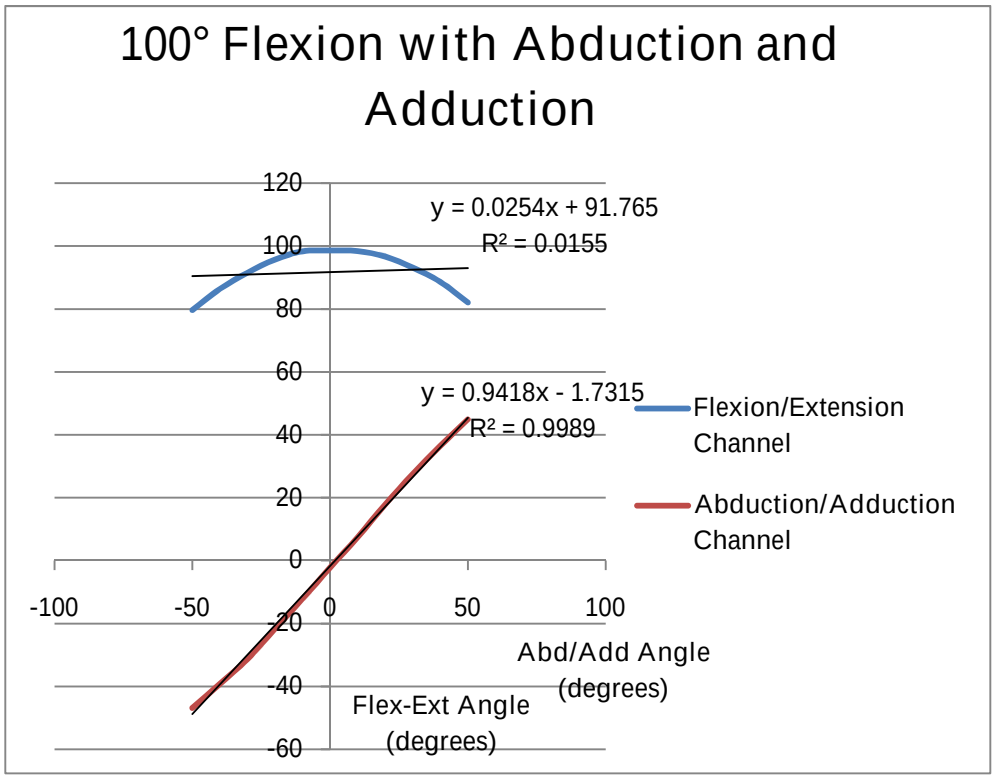
Graph 6-6: The flexible goniometer was articulated from 50° abduction through to 50° adduction whilst aligned in 40° flexion.



Graph 6-7: The flexible goniometer was articulated from 50° abduction through to 50° adduction whilst aligned in 60° flexion.



Graph 6-8: The flexible goniometer was articulated from 50° abduction through to 50° adduction whilst aligned in 80° flexion.



Graph 6-9: The flexible goniometer was articulated from 50° abduction through to 50° adduction whilst aligned in 100° flexion.

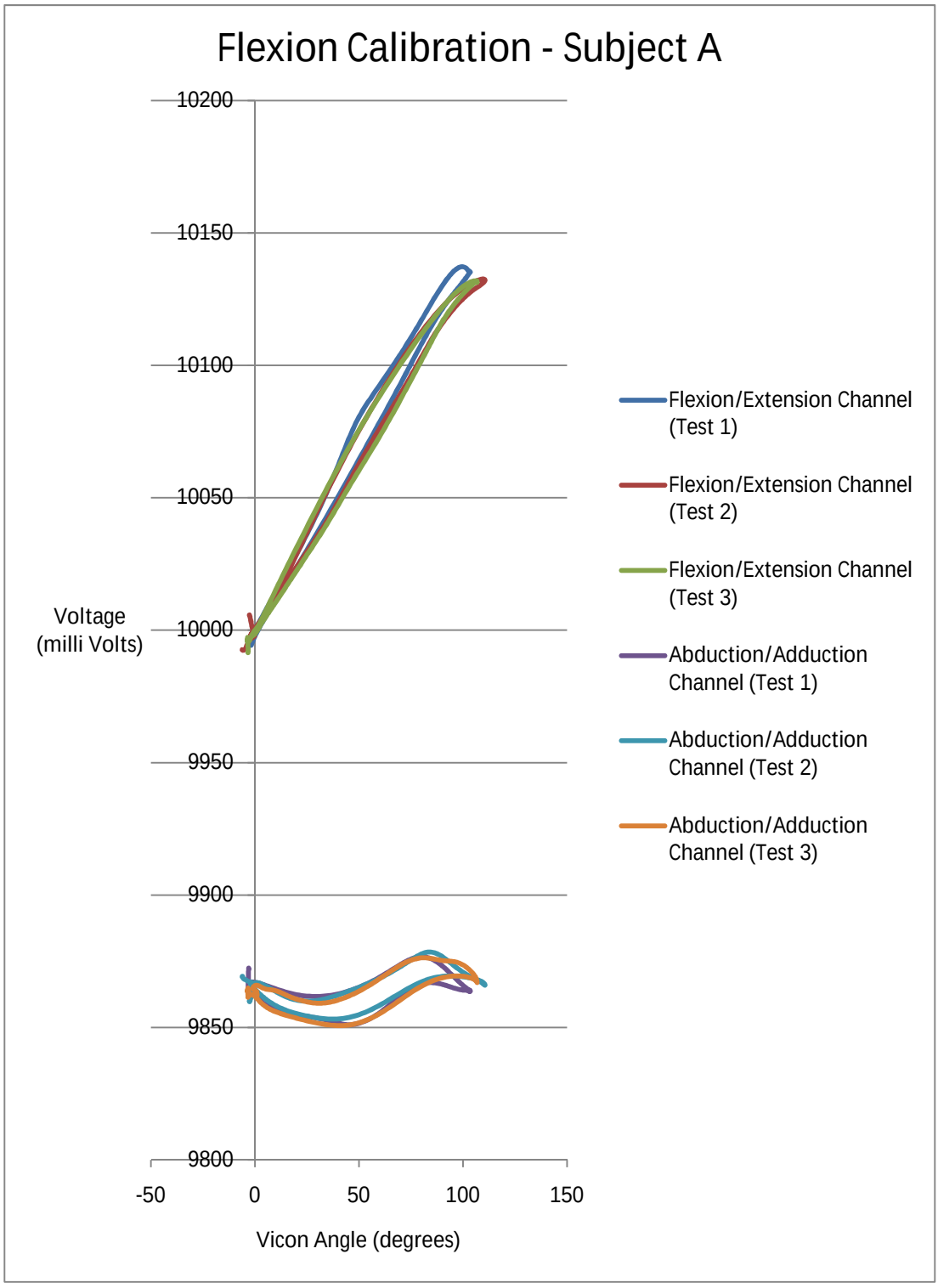
6.3. On-Subject Calibration Results

The on-subject calibration results were obtained during flexion, extension and abduction experiments. The calibration procedures were repeated three times for each articulation and an average calculated for each subject, as shown in table 6-3.

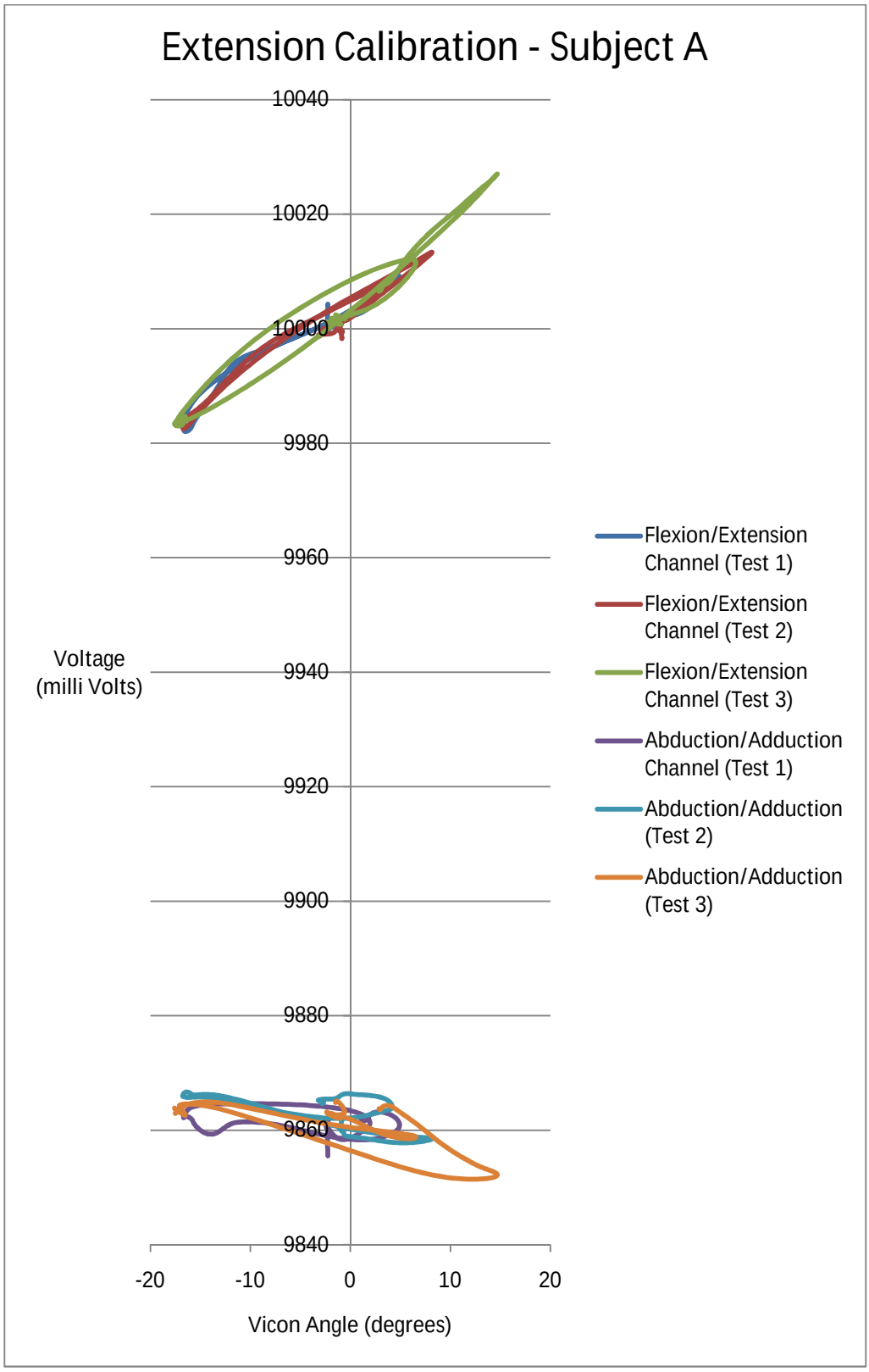
	Subject A		Subject B		Subject C	
Calibration	Channel		Channel		Channel	
Articulation	Fl/Ex	Ab/Ad	Fl/Ex	Ab/Ad	Fl/Ex	Ab/Ad
Flexion	1.30	0.038	1.49	-0.05	1.25	0.32
Extension	3.46	2.57	3.82	2.92	3.43	2.80
Abduction	0.20	-1.39	0.21	-1.182	0.20	-1.47

Table 6-3: The average calibration coefficient results for the flexion-extension and abduction-adduction channels (all values are in milli Volts/degree)

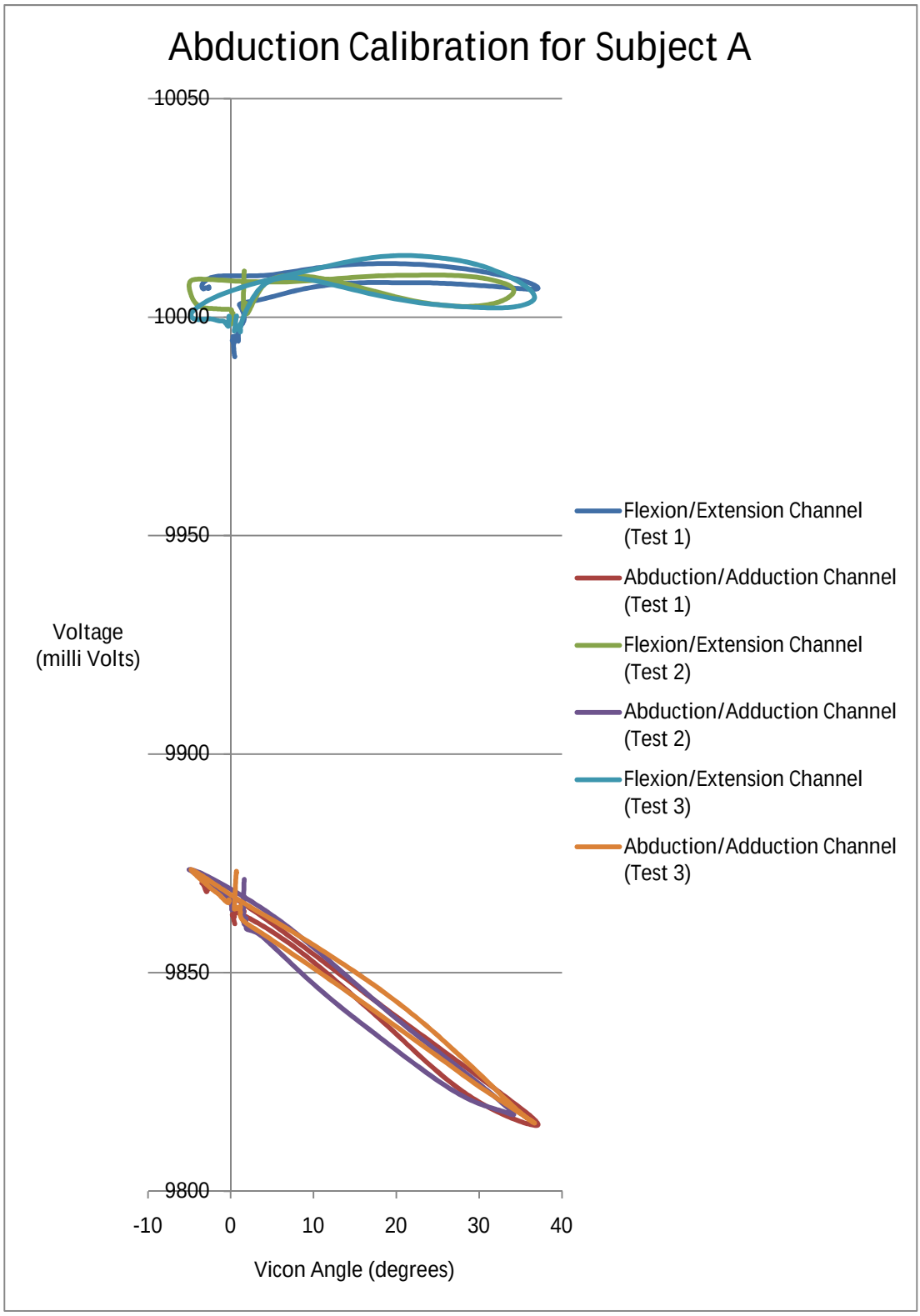
The average calibration results were found to vary between subjects, as shown in appendix A. For the purpose of further discussion only subject A's calibration results have been selected for inclusion in this section (see graphs 6-10 to 6-12).



Graph 6-10: Flexion calibration using Vicon angle measurements and flexible goniometer output voltages.



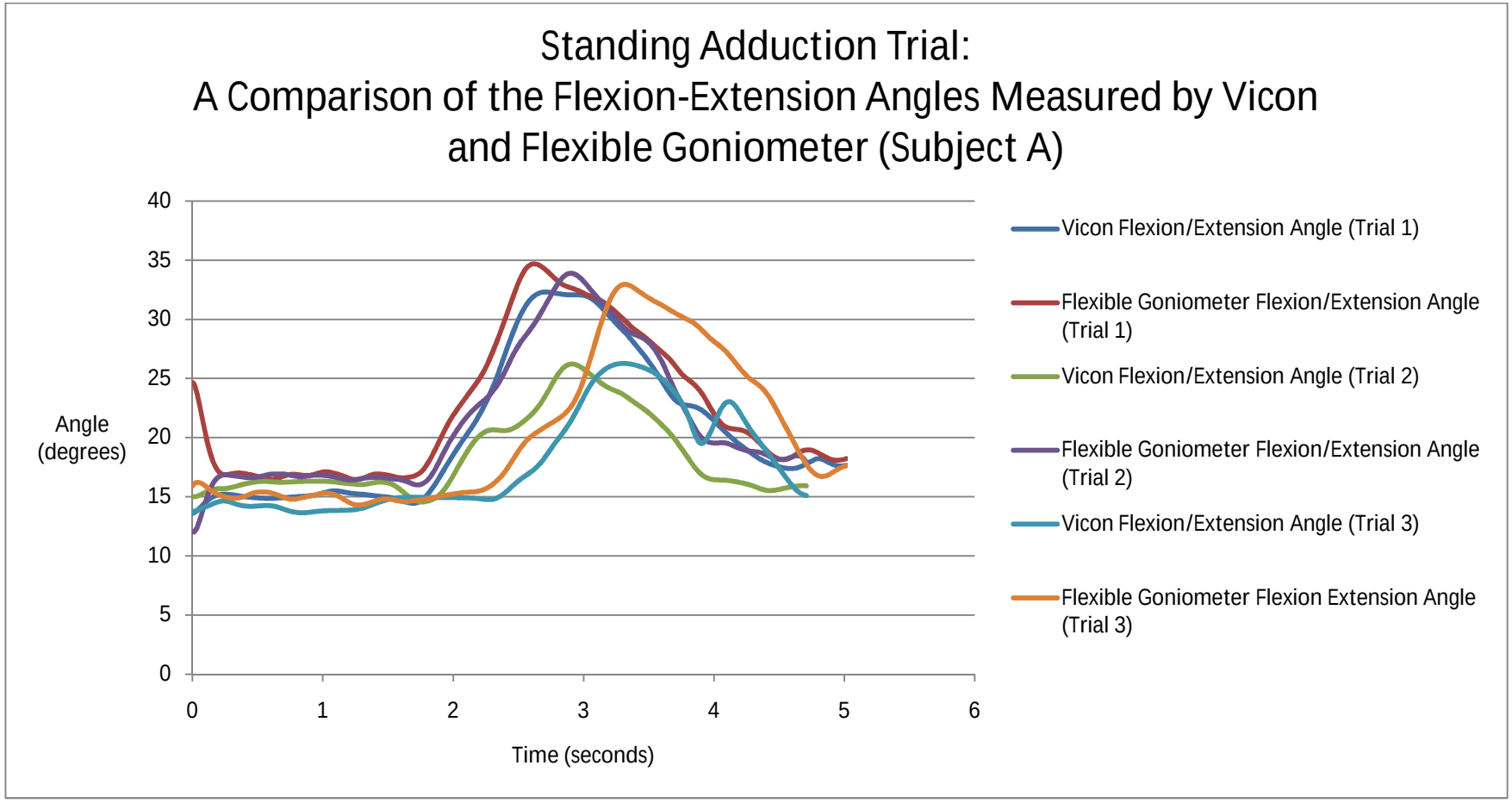
Graph 6-11: Extension calibration using Vicon angle measurements and flexible goniometer output voltages.



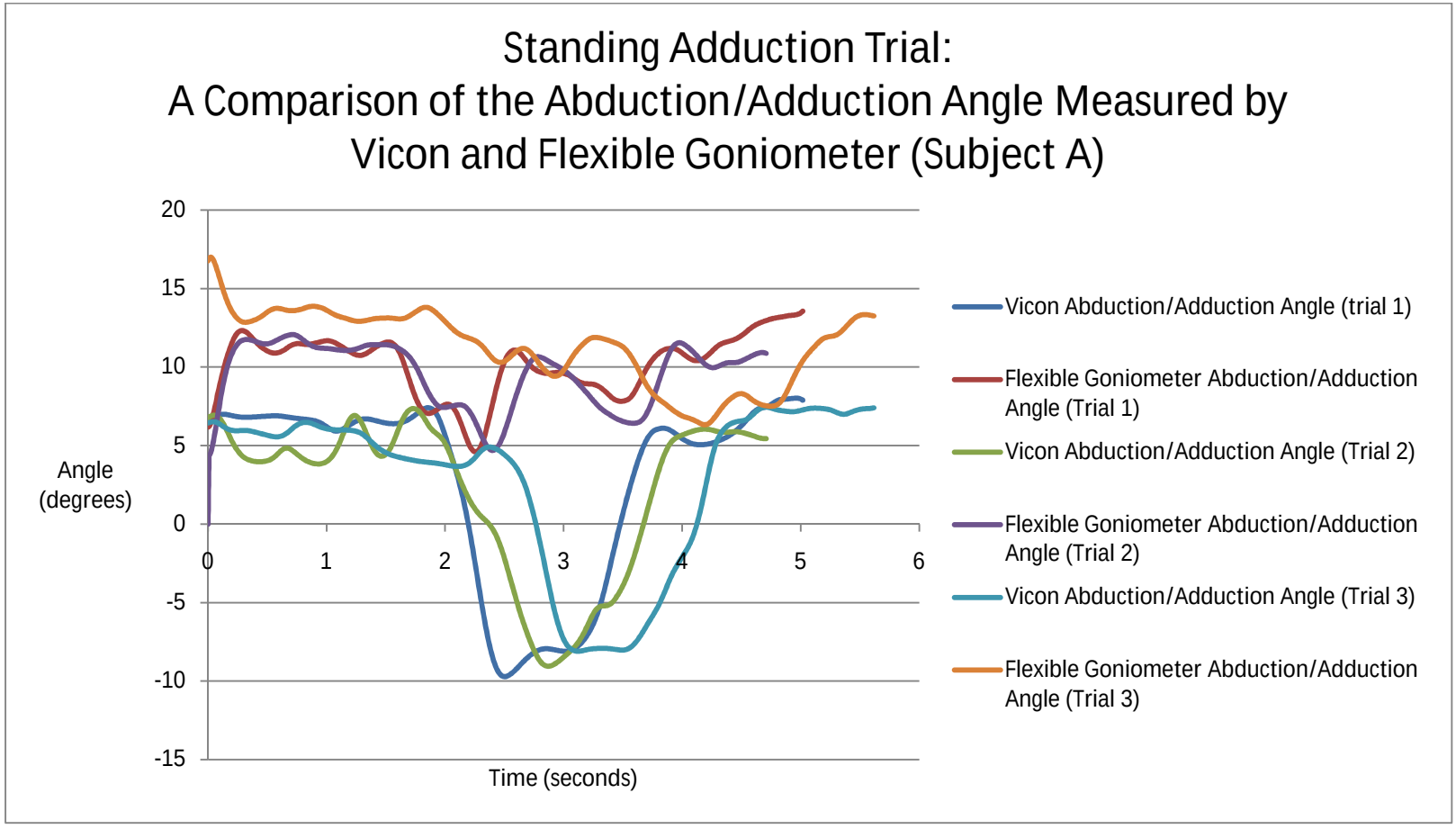
Graph 6-12: Abduction calibration using Vicon angle measurements and flexible goniometer output voltages.

6.4. On-Subject Validation Results

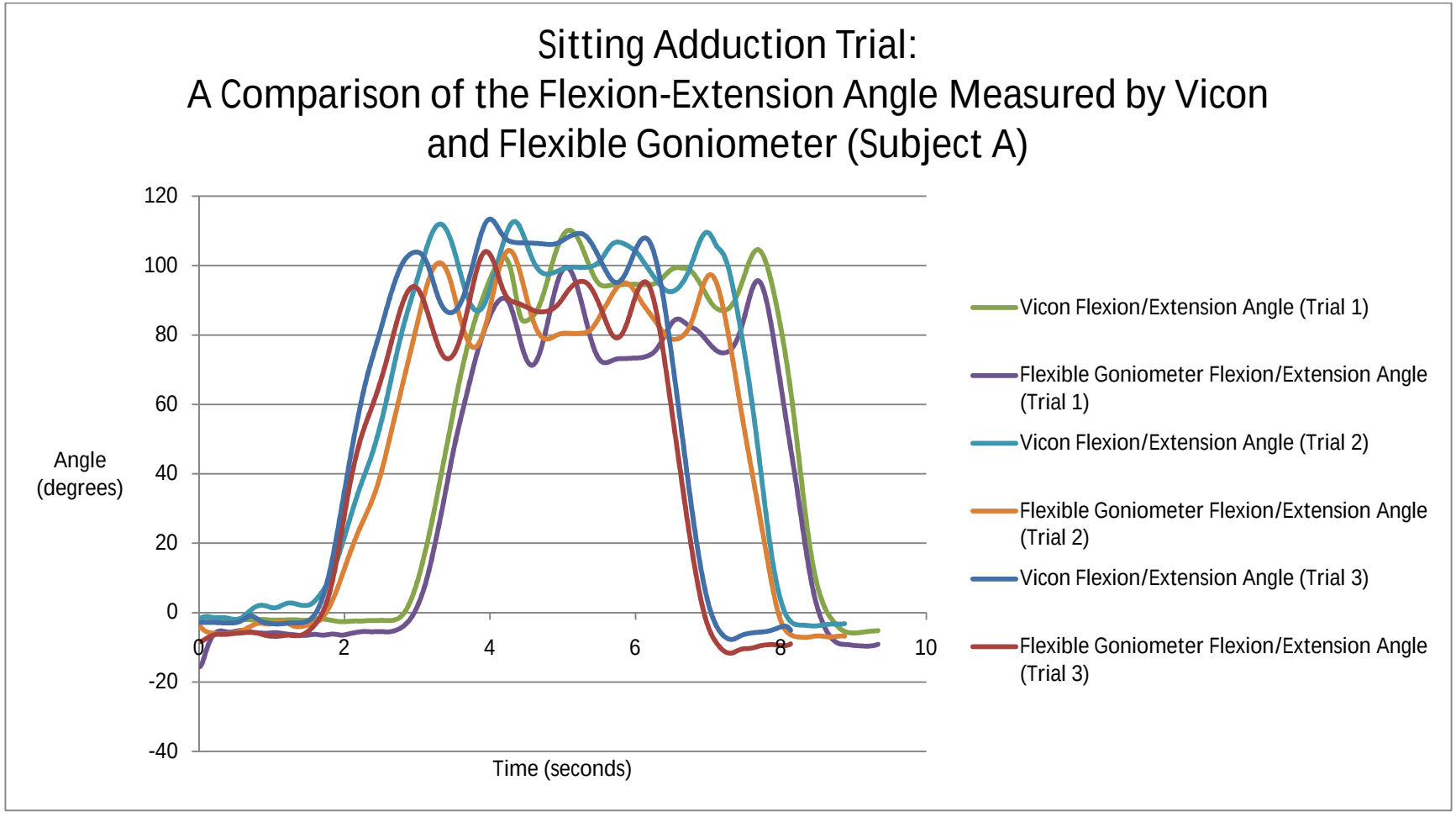
As discussed in section 5-7, two different on-subject validation trials were used to compare the measured flexible goniometer angles with those of the Vicon system; a standing adduction and a sitting adduction trial. Again, for the purpose of discussion only subject A has been presented in this section, however, full results for subject B and C are presented in appendixes C and D.



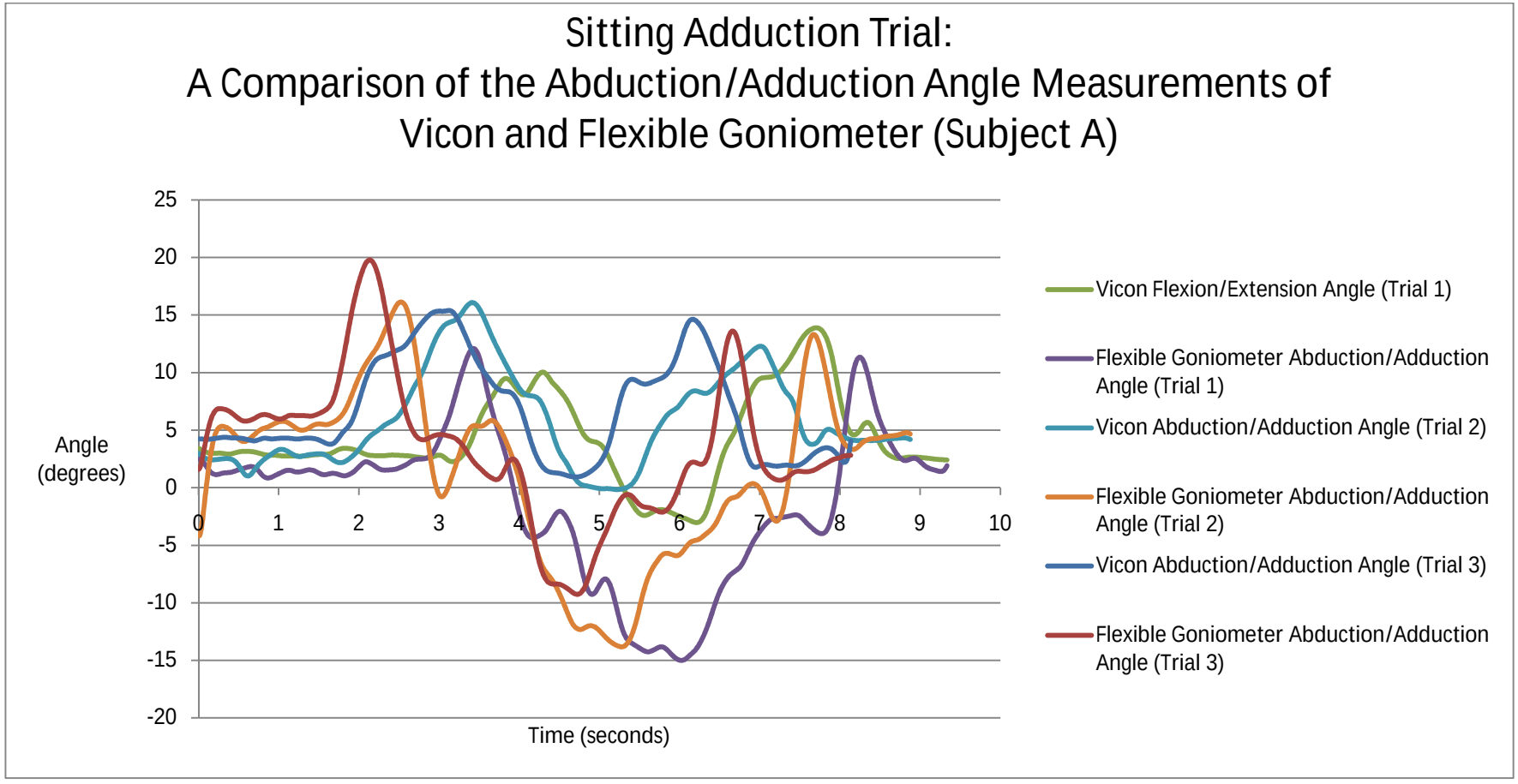
Graph 6-13: The flexion/extension angles measured by Vicon and the flexible goniometer during the standing adduction trials for Subject A.



Graph 6-14: The abduction/adduction angles measured by Vicon and the flexible goniometer during the standing adduction trials for subject A.



Graph 6-16: The flexion/extension angles measured by Vicon and the flexible goniometer during the sitting adduction trials for subject A.



Graph 6-17: The abduction/adduction angles measured by Vicon and the flexible goniometer during the sitting adduction trials for subject A.

Chapter 7: Discussion

The development of an alignment alert system to inform a hip arthroplasty patient that they are about to enter a position of high risk to dislocation was initially thought to require a sensor with a ±5° degree accuracy in the flexion/extension and ±2° in abduction/adduction planes during combined angular movements. With this requirement of accuracy in mind several joint angle measurement sensors were investigated to decide which would be most suitable for the application of a hip articulation alert system. The sensors reviewed included manual goniometers, triaxial potentiometers, flexible goniometers, gyroscopes and accelerometers. A comparison identified the flexible goniometer as potentially being the most suitable for this application. The attractive attributes of the flexible goniometer which led to its selection were:

- Reported high degree of accuracy
- Accurate location of the anatomical joint centre was not required.
- Light-weight.
- Low bulk.
- Unrestrictive.

The aim of the study was to evaluate whether a Biometrics SG150 flexible goniometer could be used to measure the combined movements experienced

at the hip joint using both bench and on-subject calibration and validation experiments.

7.1. Bench Calibration

Bench calibration of the goniometer enabled evaluation of the output linearity and identification of the cross-talks of both channels (graphs 6-1 and 6-2). The principal channels for each calibration, when fitted with a best-fit line, had a coefficient of determination (R^2) value in excess of 0.99. This indicates a highly significant and linear correlation between the true angle and the goniometer output voltage. These findings supported those by Rowe et al (2001).

The magnitudes of the cross-talks during calibration were of the order of 1.98% and 1.02% during flexion-extension and abduction-adduction calibration respectively.

7.2. Bench Validation

The hip joint, being a triplanar joint, was capable of flexion-extension, abduction-adduction, and internal-external rotation therefore the cross-talk effects of such movement require evaluation to ensure they did not affect the output results excessively. Due to the time constraints of this study only the effects of combined flexion-extension and abduction-adduction were

examined, however, Rowe et al (2001) have documented internal-external rotation to induce a systematic cross-talk of 3% at 60° rotation during calibration.

The results obtained for the validation experiments (graphs 6-3 to 6-9), where abduction-adduction occurred with simultaneous flexion-extension, showed increased cross-talk with larger angles of combined articulation. The cross-talk produced at 50° abduction or adduction (the maximum tested) combined with 40°, 60°, 80° and 100° degrees of flexion was 2.5%, 3%, 8% and 10% respectively. This can be identified in graphs 6-3 to 6-9 as an increasing curvature of the flexion-extension calibrated output with increasing abduction or adduction angle. These cross-talk errors are supported by Rowe et al (2001) who documented 8° to 10° of error at 120° of flexion and 45° abduction.

7.3. On-Subject Calibration

The on-subject calibration (section 5-6) was a more difficult calibration experiment to design. A calibration requires only principal axis articulation, where there are ideally no involuntary movements in any other plane. The physiological ball-and-socket design of the hip joint makes obtaining pure flexion-extension or abduction-adduction very difficult. Appendix B shows the angular movements produced at the hip joint during calibration as measured by the Vicon motion analysis system. Subject A exhibited on average 4°, 9° and 11° of involuntary axis movement during the 17° extension, 108° flexion and 35° abduction calibration movements

respectively. For the ease of calculating the measured angles using the calibration matrix it was assumed that the involuntary movements did not produce significant errors, however, the author is aware of the errors that were produced by an imperfect experimental technique.

The subject (table 6-3) and bench (table 6-2) calibration coefficients differed when compared. The flexion calibration coefficients in the principal channels were 1.30, 1.50 and 1.25 for subjects A, B and C respectively, compared to 1.89 during the bench calibration. This represented a difference of 34% between subject C and the bench calibration coefficient. In the case of inter subject comparison, the difference between subjects B and C was 16%. This indicates that each subject requires individual calibration on being fitted with the goniometer. There are a various reasons which may explain the variation in the calibration results:

- Positioning of the flexible goniometer may have varied amongst subjects, with different locations of the goniometer end-blocks influencing the angle measured by the goniometer.
- Inter-subject variation of soft tissue volume may have influenced the deformation of the tissues which could either exert abnormal force upon the strain gauge cable producing errors or, alternatively, prevent rotation with the underlying boney anatomy.
- Skin movement of the reflective markers used by the Vicon system may have produced errors in the location of the local reference system. The subsequent angles calculated using the model would have produced errors in the true hip joint angle. An increasing

amount of skin movement would have been produced with larger angles of hip position.

- Movement of the lycra shorts where the goniometer was attached would produce motion artefacts.
- Poor calibration experimental technique where the subjects exhibited different degrees of involuntary movement influenced the accuracy of the calibration results which were later used during validation.

Examination of the calibration results when plotted (graphs 6-10 to 6-12 and appendix A) showed what appeared to be hysteresis effects during each articulation. Whilst there may have been some hysteresis, a more likely explanation was that the subject was not articulating along the same path on the outward and return flexion, extension or abduction calibration movements. This theory was supported by the results shown in the graphs in appendix B where biplanar motion was clearly identified. As a result this was a significant flaw in the calibration process, and affected the overall accuracy of the measurement device. Ideally, a specially designed frame would be developed to maintain the articulating limb on the correct plane during calibration. Other factors which could have contributed to errors were soft tissue deformation, skin motion and motion artifact due to movement of the shorts.

7.4. On-Subject Validation

In an attempt to validate the accuracy of the flexible goniometer when measuring hip angles, a standing and sitting, flexion with adduction trial was carried out. These were also alignments which are associated with an increased risk of dislocation.

The standing-adduction trial began in approximately 15° of hip flexion and the test limb was then adducted anterior to the supporting limb (see figure 5-7). Subject A's results were examined (see appendix C for all subject results) to compare the flexion–extension results for the flexible goniometer to the Vicon measurements (graph 6-13). The average maximum error was 18.5% with the flexible goniometer over estimating the flexion angle in each trial. The abduction-adduction channel (graph 6-14) showed particularly poor correlation with the Vicon system. The results obtained for the abduction/adduction channel of the goniometer were significantly inaccurate and could not be interpreted well as a result. Possible causes of these errors could be cross talk effects on the goniometer when large combined angles are applied. Alternatively, soft tissue deformation may reduce the angular displacement experienced by the goniometer, affecting the angle measured.

The sitting-adduction trial results involved significantly larger combined articulations of the hip joint. The hip was flexed to approximately 90° to achieve sitting and then increased further to achieve a cross-legged position. The flexion-extension channel (graph 6-15) showed significant errors when compared to the Vicon system. The goniometer under measured the

maximum flexion angle by approximately 23%. This is in contrast to the standing-adduction trial where the flexible goniometer was over estimating the flexion-extension angle by a similar value. The abduction-adduction angle of the hip joint showed poor correlation between the Vicon system and the goniometer. This may be due to the potential for deformation of soft tissue during sitting, particularly around the waist and hips.

Chapter 8:
Conclusion and Future Work

The aim of this study was to validate a biaxial flexible goniometer for use in the measurement of hip alignment. This was achieved through using both bench and on-subject calibration and validation experiments.

Bench calibration of the goniometer identified a highly significant and linear correlation between the flexible goniometer outputs and the measured angle. Cross-talks were calculated to be in the order of 1-2%.

Bench validation examined the effects of combined flexion or extension with abduction or adduction. For small angles of abduction or adduction when combined with flexion or extension there was no problem. However, with increasing abduction or adduction angles in excess of 20° combined with flexion or extension angles in excess of 40°, errors were produced which significantly reduced the accuracy of the measured angle. In the case of 100° flexion with 50° abduction there was an average error of 8%. This supports Rowe et al (2001) who identified an 8% error at 120° flexion and 40° abduction.

Calibration of the flexible goniometer on the subject produced significantly different calibration coefficient values from those of the bench calibration.

This was thought to be due to soft tissue deformation, skin movement and errors in experimental calibration technique. The soft tissue deformation and skin movement was of particular concern due to the potentially erroneous movements of the flexible goniometer distal and proximal blocks, as well as the reflective markers used by the Vicon system. These errors were thought to be increased significantly at greater ranges of flexion and abduction where the soft tissues tend to bulge.

Validation of the flexible goniometer on the subject was carried out during a sitting and standing trial, where the subject flexed and adducted the hip joint simultaneously. The flexion and extension angles measured with the flexible goniometer showed good correlation with the Vicon system, however, errors were of magnitude of 18% and 23% during the standing and sitting trials respectively. The adduction and abduction measurements were less accurate, with the flexible goniometers significantly underestimating the adducted position. The level of error was difficult to identify due to the poorly correlated signals. Similar to the on subject calibration, the errors were thought to have been primarily induced by soft tissue deformation and skin motion, as well as experimental errors due to involuntary movements during calibration.

In terms of clinical application, the errors indentified during large combined movements within the flexible goniometer, as well as soft tissue and skin movement when fitted to a subject, produced errors in excess of the originally recommended ±5° flexion/extension and ±2° abduction/adduction. An activity where this could pose a greater risk to dislocation for a hip

arthroplasty patient would be during cross-legged sitting where there would be a large combined hip flexion and adduction angle. In order to accommodate the larger than originally anticipated flexible goniometer errors, the upper positional limits could be reduced to ensure the subject still stayed within the safe range of motion. The flexion limit could be set at 80° to allow for 10° of measurement error, ensuring the subject did not exceed 90° flexion where they are at a much greater risk of dislocation. Similarly, the adduction limit could be reduced to allow for ±5° error instead of the originally hypothesized ±2°. Overall, a reduction in the safe range of motion limits could still help patients maintain a safe alignment whilst still maintaining a large functional range of hip motion.

There was, to the author's knowledge, no other research available which examined the use of biaxial flexible goniometers in the measurement of hip joint position. This study may therefore help provide some evidence based research to support the manufacturers proposed application of the flexible goniometer for measurement of hip joint position. Several studies, including those by Rowe et al and Jonsson and Johnson, examined the use of biaxial flexible goniometers in the measurement of joint motion. However, the joints examined had always been primarily uniplanar with only small degrees of secondary plane motion. The results obtained during this study identified the positive and negative aspects of using a biaxial flexible goniometer to measure hip joint position, where the hip was capable of large degrees of combined movement.

Further work could be undertaken into assessing the effects of soft tissue deformation and skin motion. This appears to be the biggest issue with regards to obtaining accurate angular measurements of the hip joint. The effect which this movement has upon the accuracy of Vicon measurements is also of interest. Improvements could be made with a redesign of the on subject calibration experiments. The articulation of the hip by articulating the hip passively, or with use of a frame, may reduce errors incurred by involuntary movements.

In conclusion, the flexible goniometer required a reduction in the position alert limits to ensure the hip joint would be maintained within a safe alignment. The soft tissue deformation, skin motion, goniometer positioning, calibration errors due to involuntary movements, and lycra shorts movement all combine to give increasing errors. Alternative solutions which may hold some promise are gyroscopes and accelerometers, both of which may be capable of more secure attachment to the subject.

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Chapter 9: BIBLIOGRAPHY

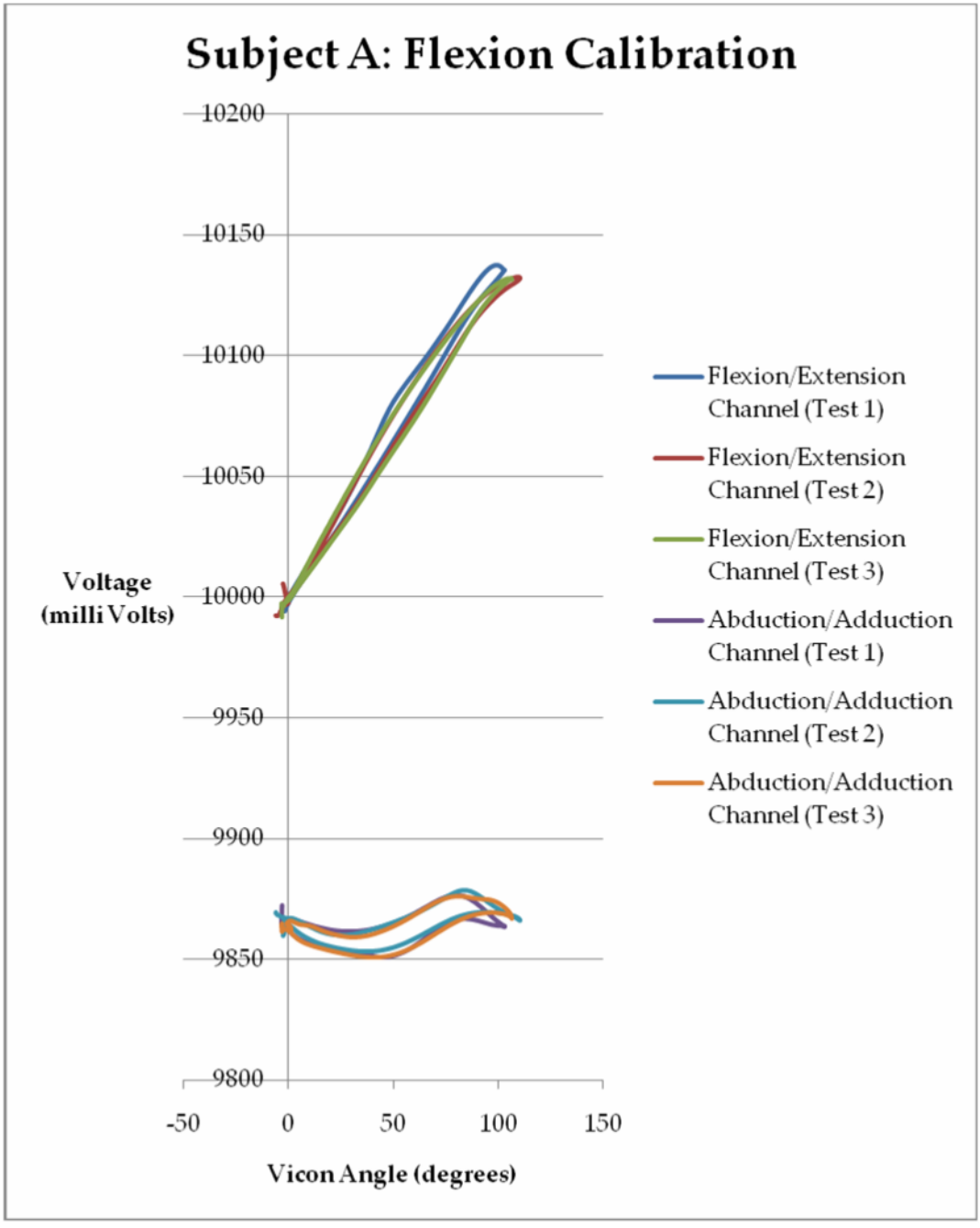
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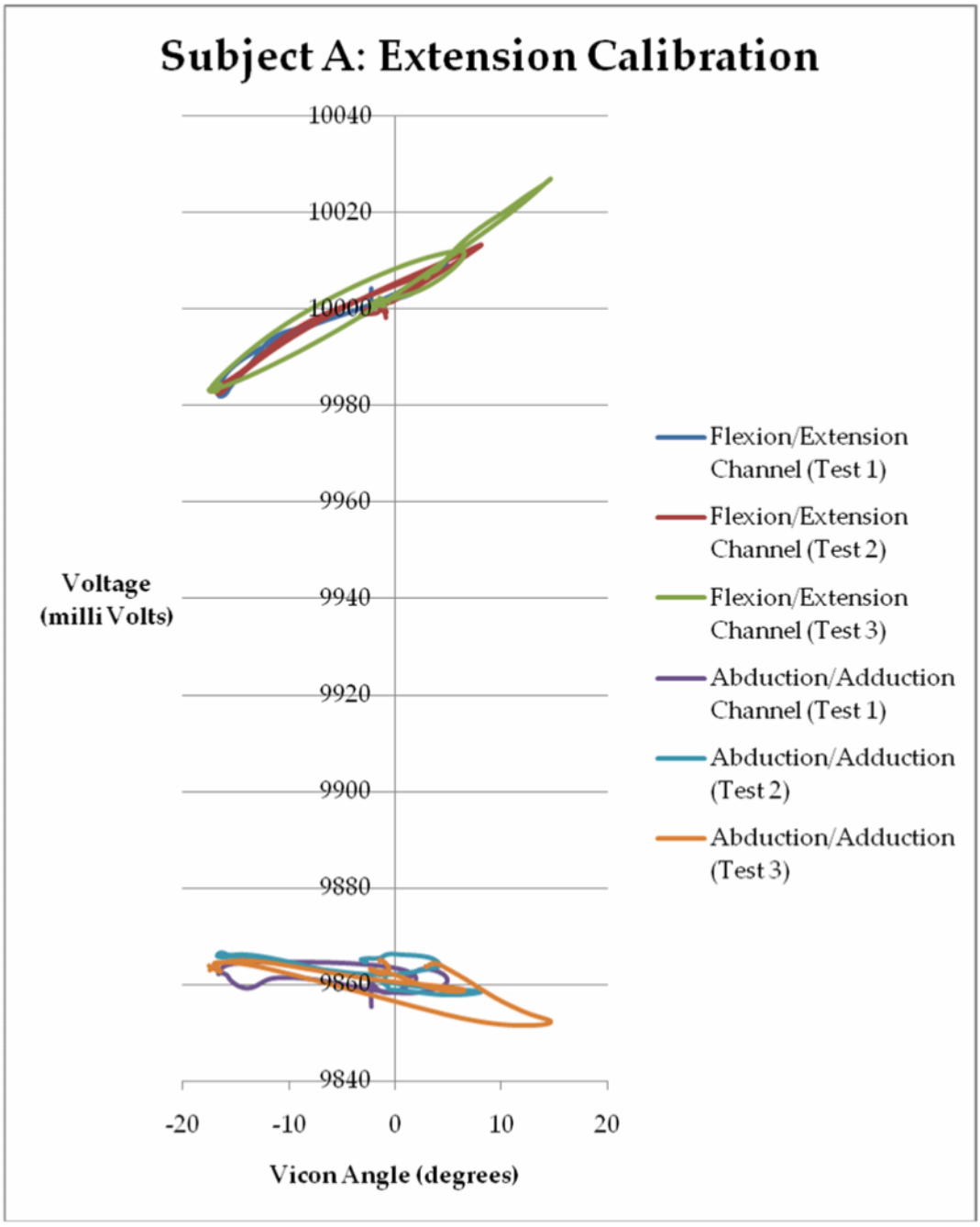
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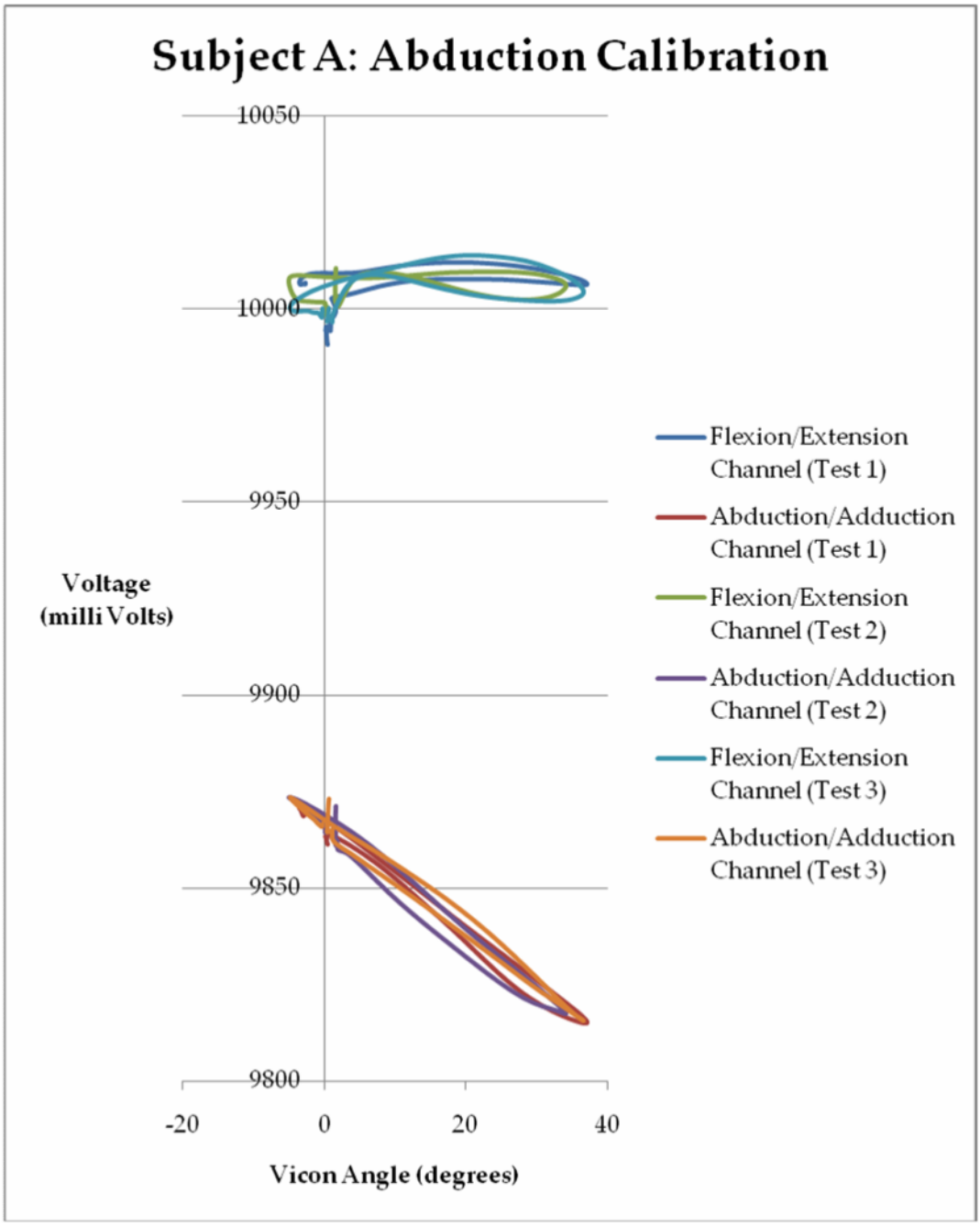
Appendix A: SUBJECT CALIBRATION RESULTS



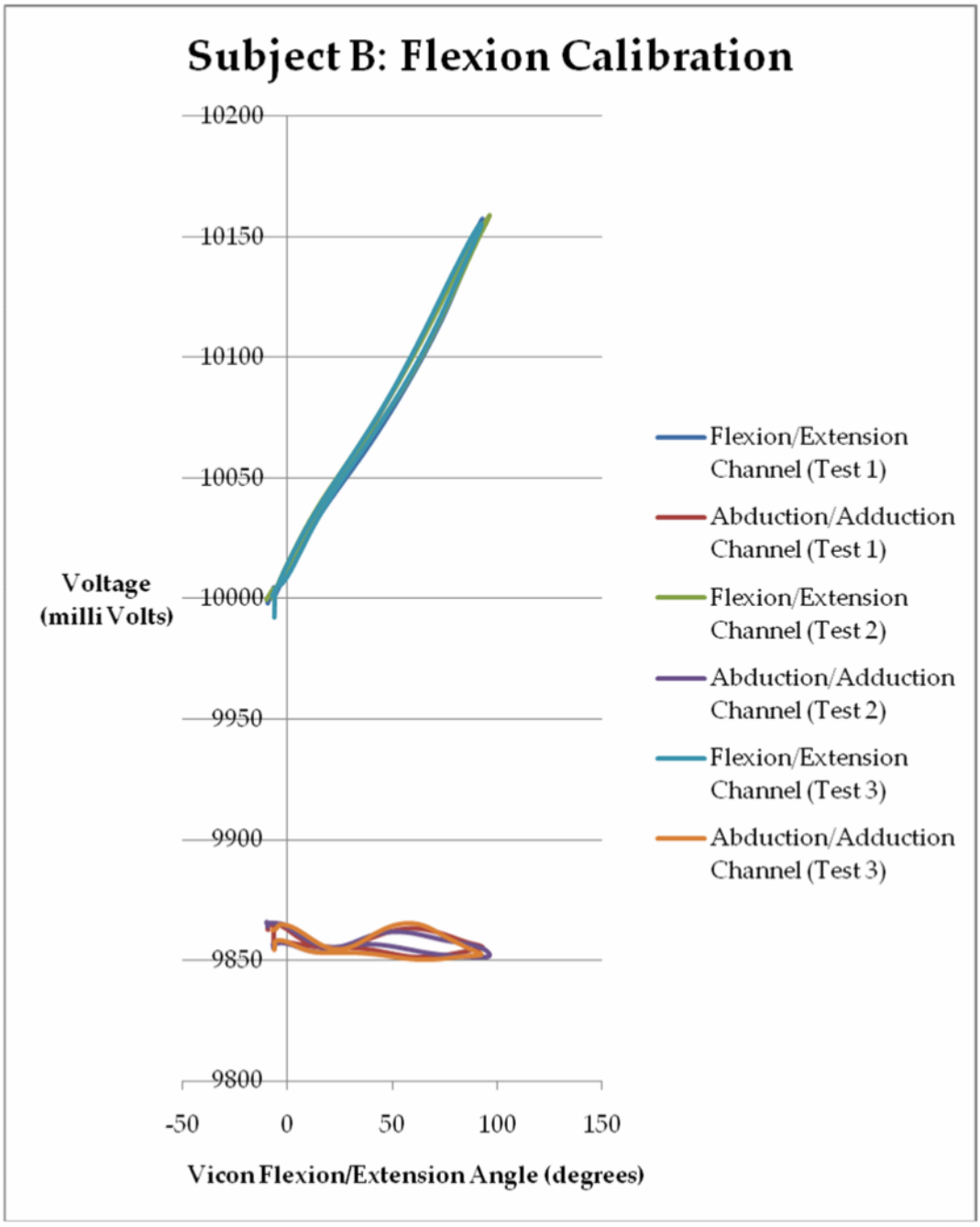
Graph 10-1: Flexion calibration results for subject A



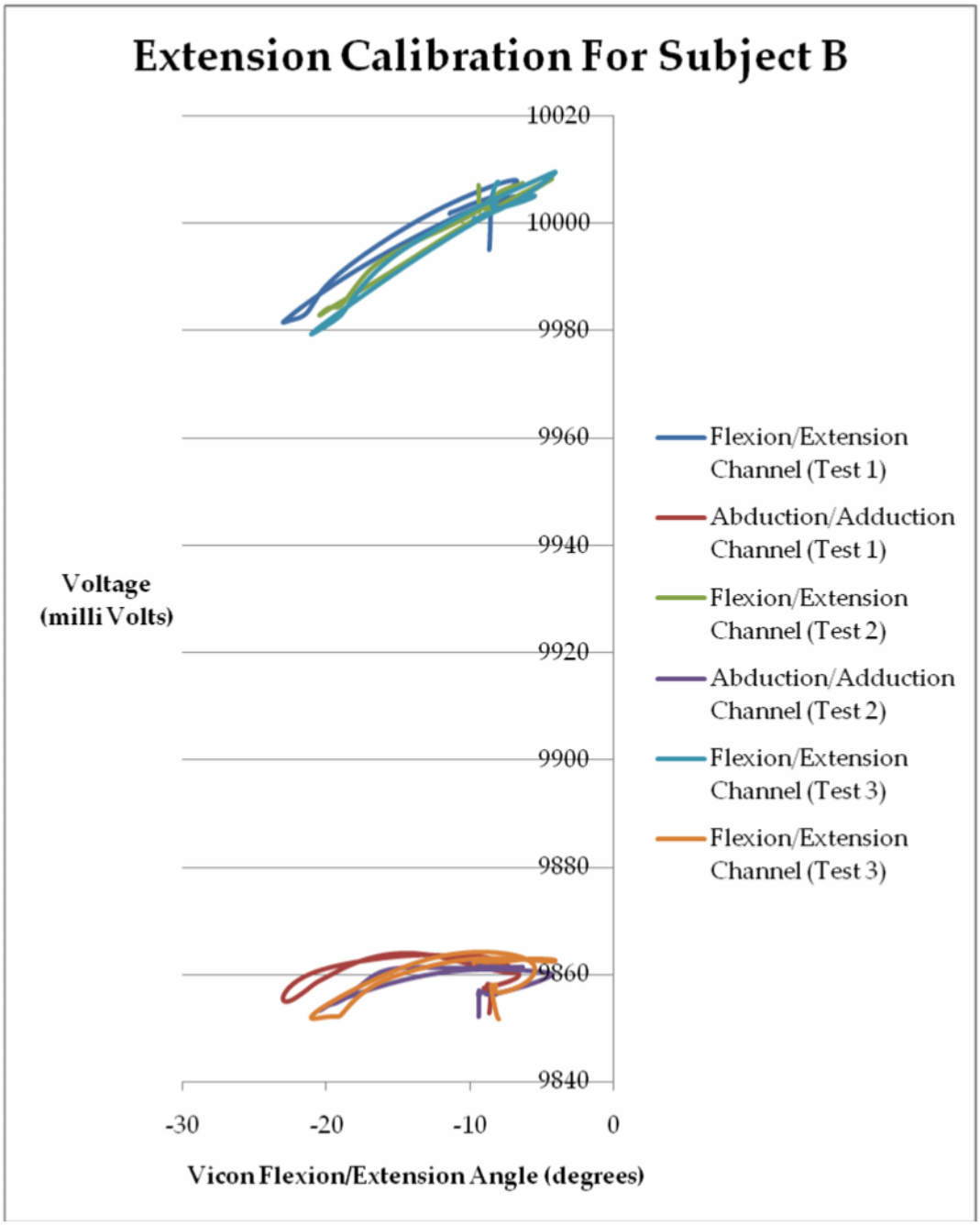
Graph 10-2: Extension calibration results for subject A



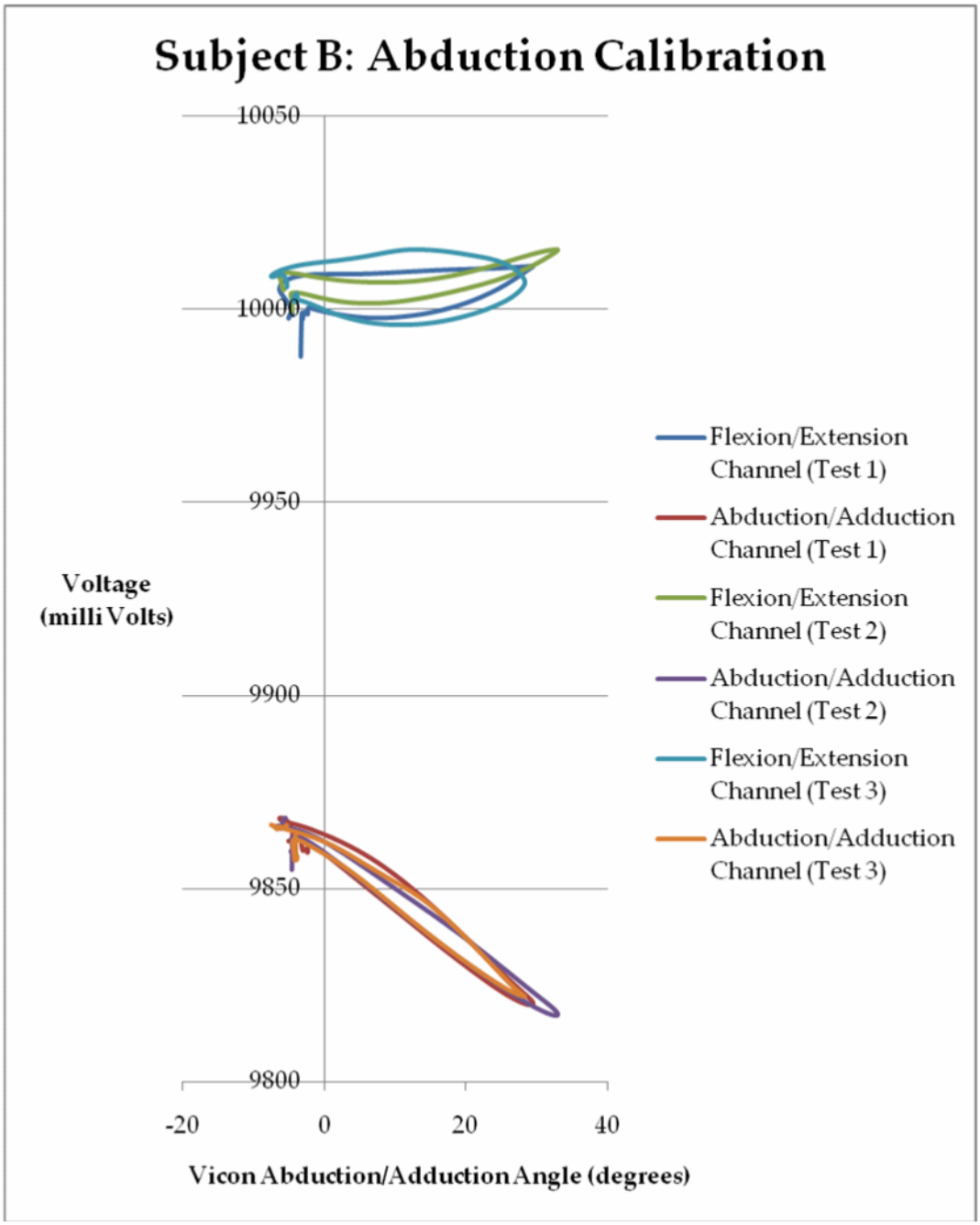
Graph 10-3: Abduction calibration results for subject A



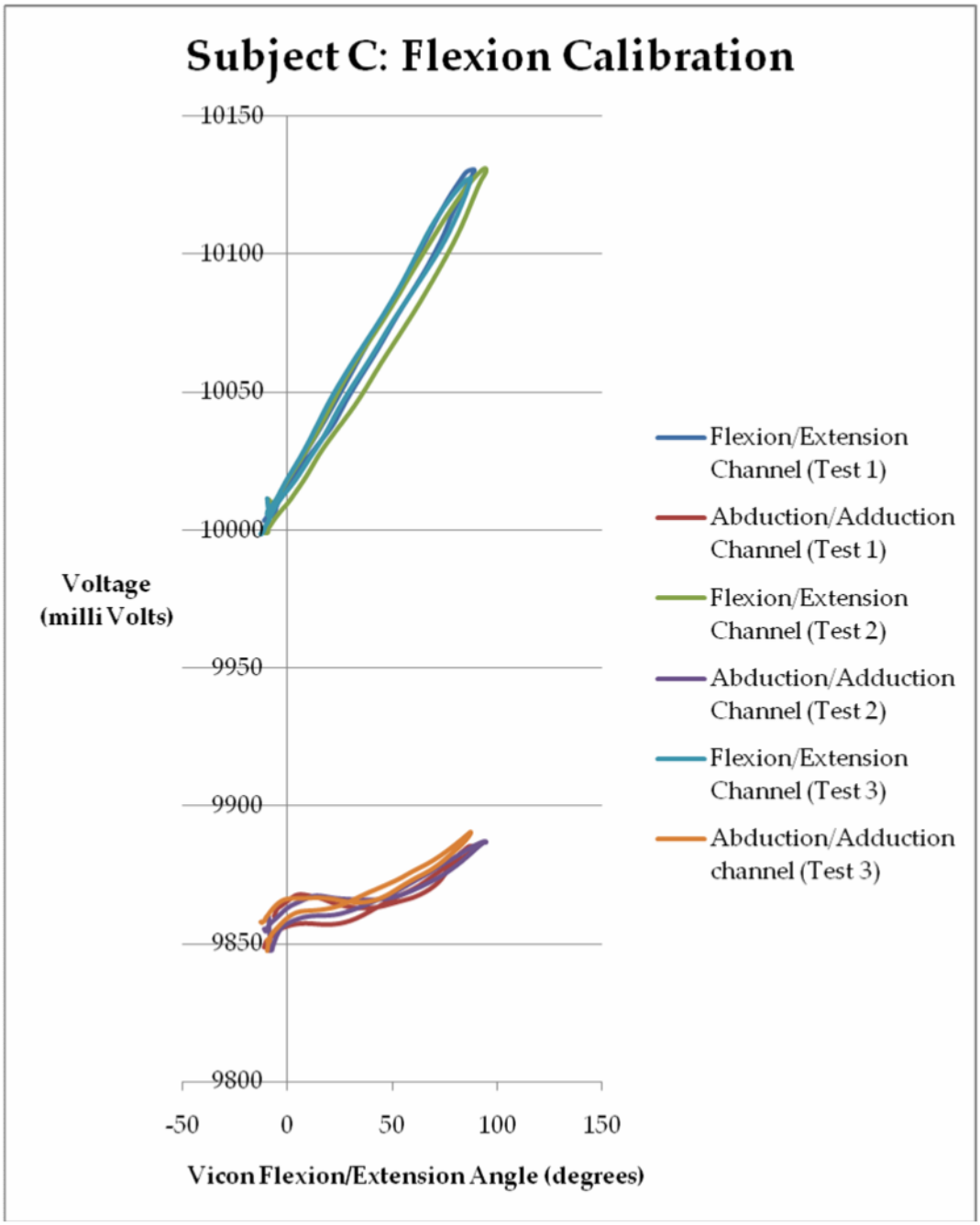
Graph 10-4: Flexion calibration results for subject B



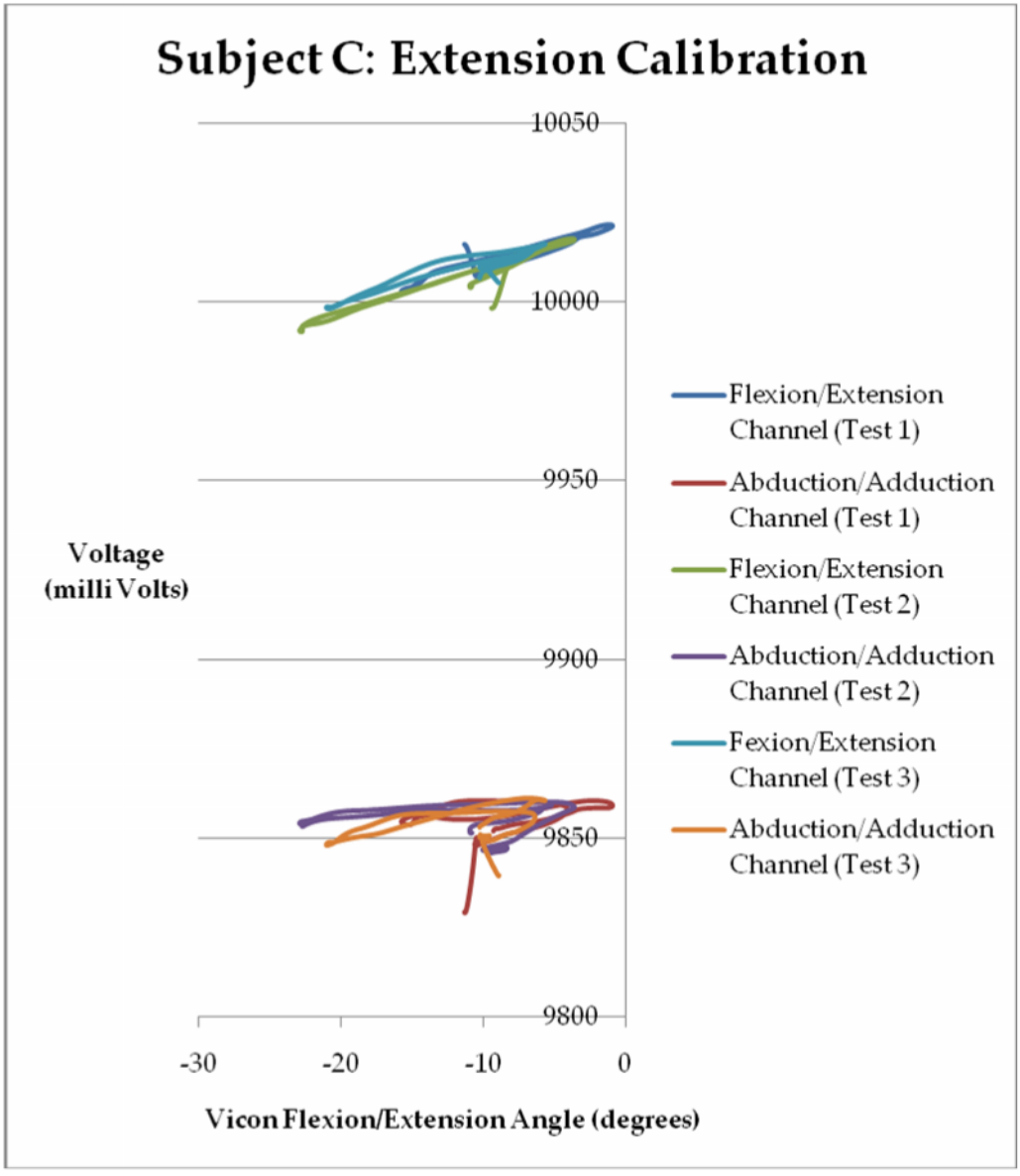
Graph 10-5: Extension calibration results for subject B



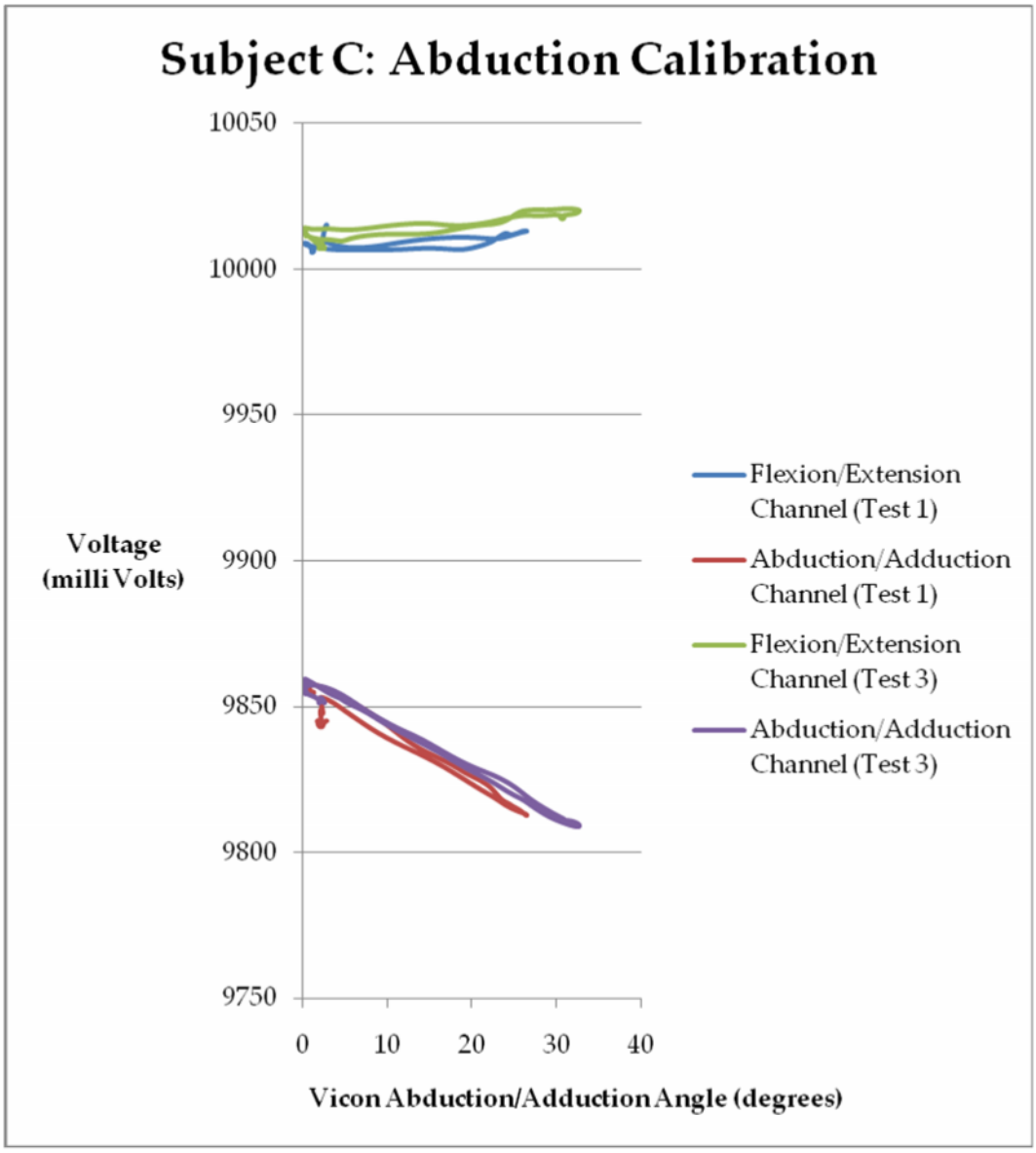
Graph 10-6: Abduction calibration results for subject B



Graph 10-7: Flexion calibration results for subject C



Graph 10-8: Extension calibration results for subject C

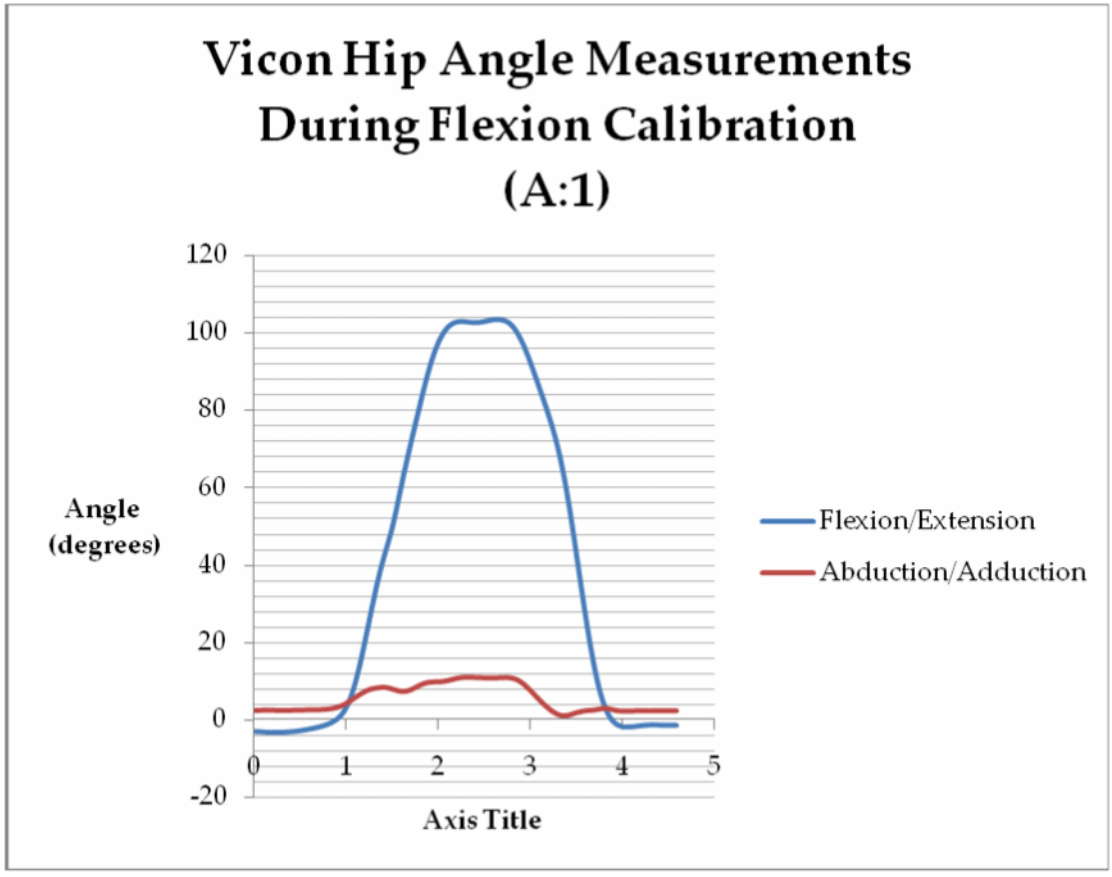


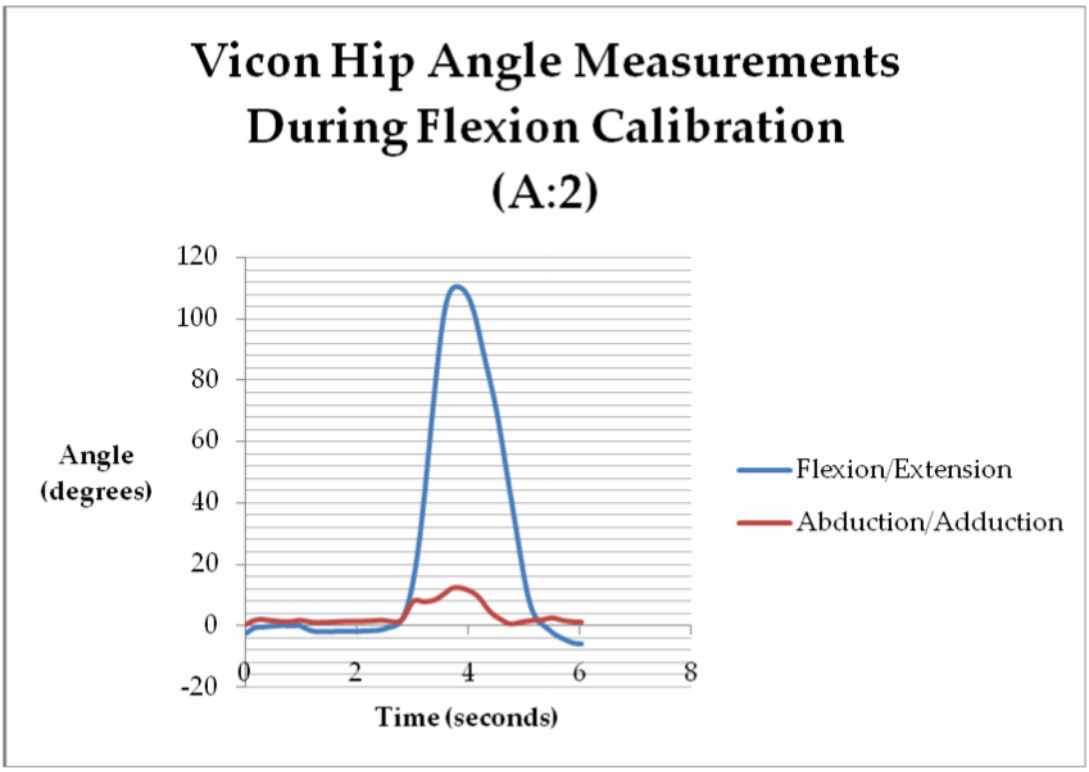
Graph 10-9: Abduction calibration results for subject C

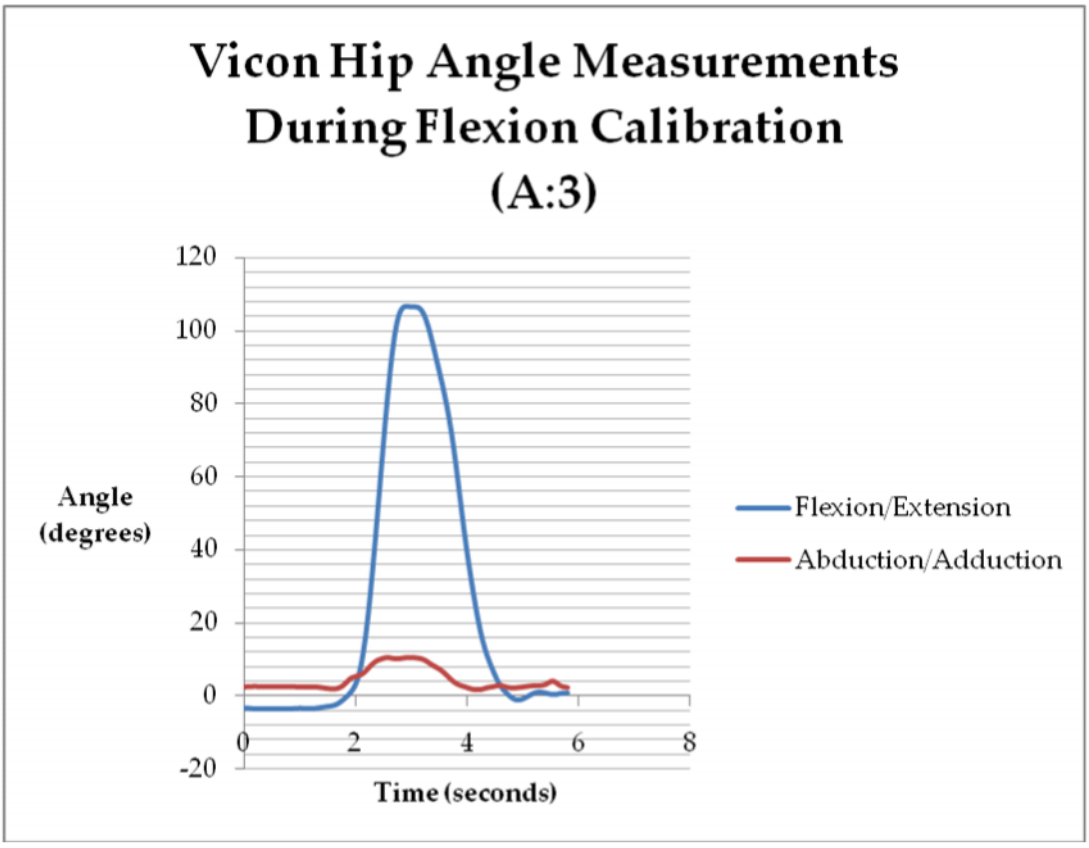
Appendix B:
HIP ARTICULATIONS DURING CALIBRATION

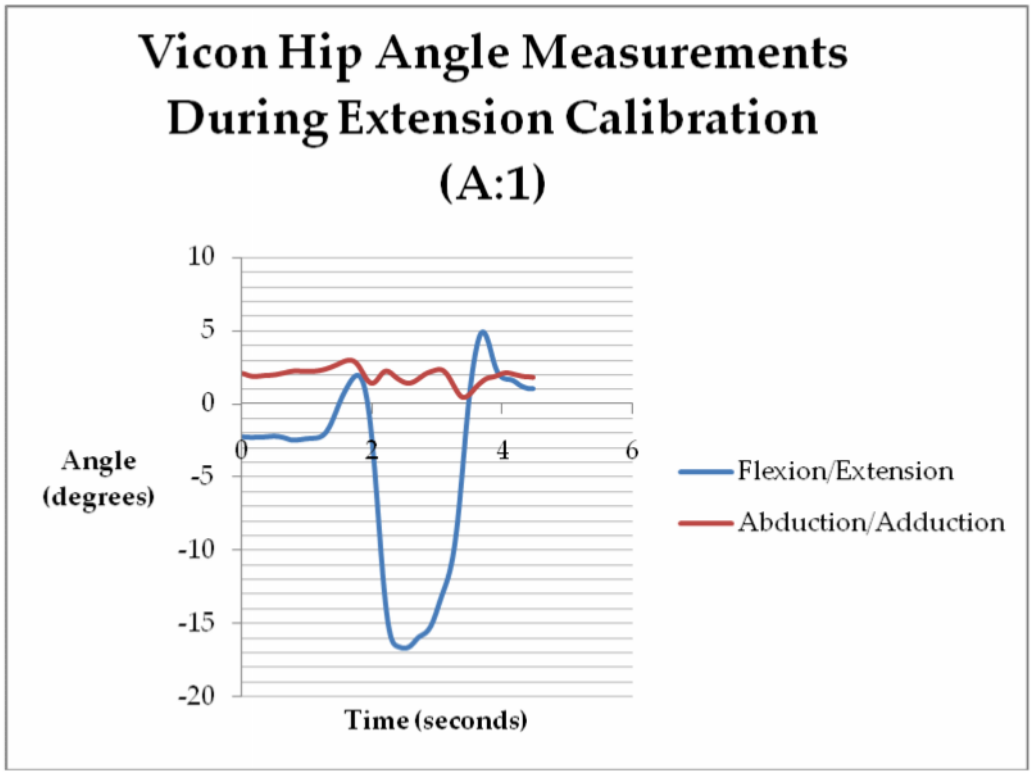
The following graphs show the articulations which were taking place during calibration, as measured by the Vicon® system. Each of the graphs is identified using an abbreviation system in brackets:

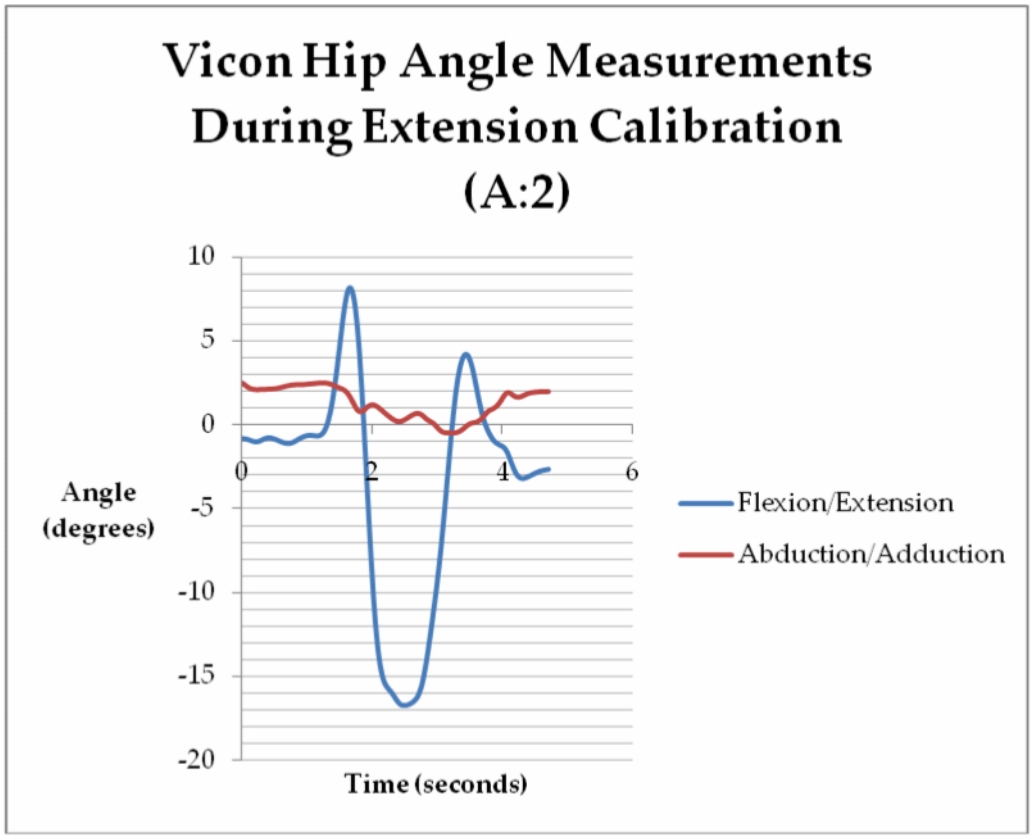
(Subject: Trial number)

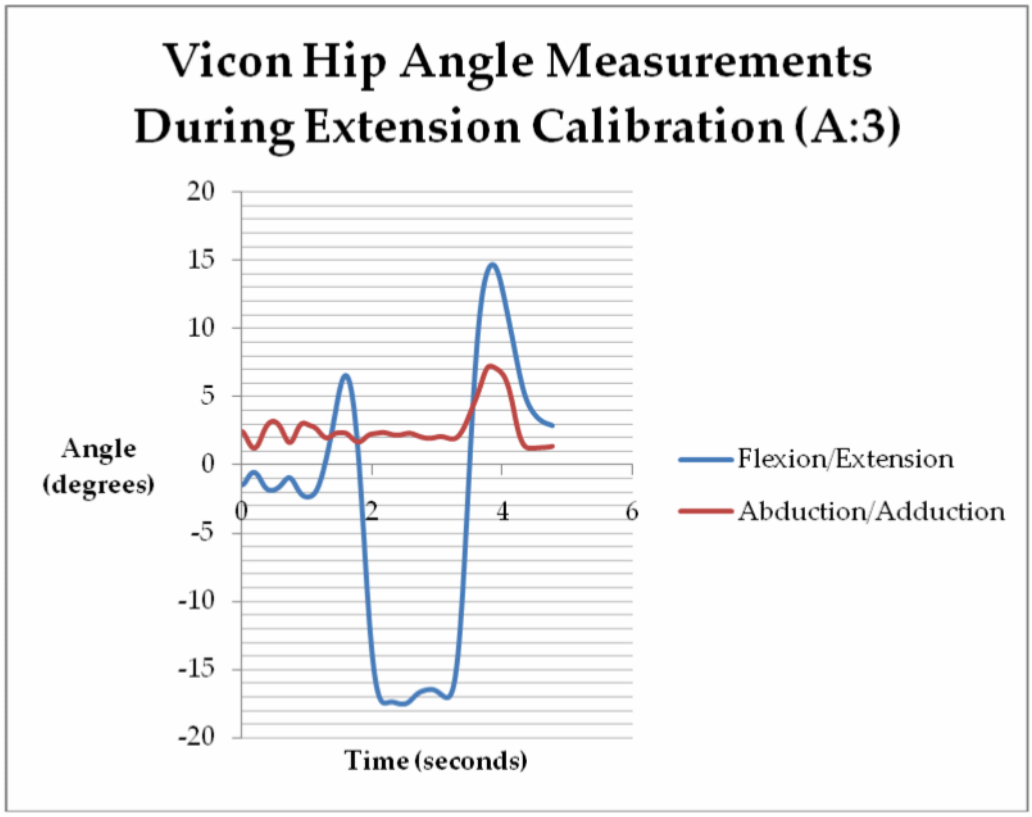


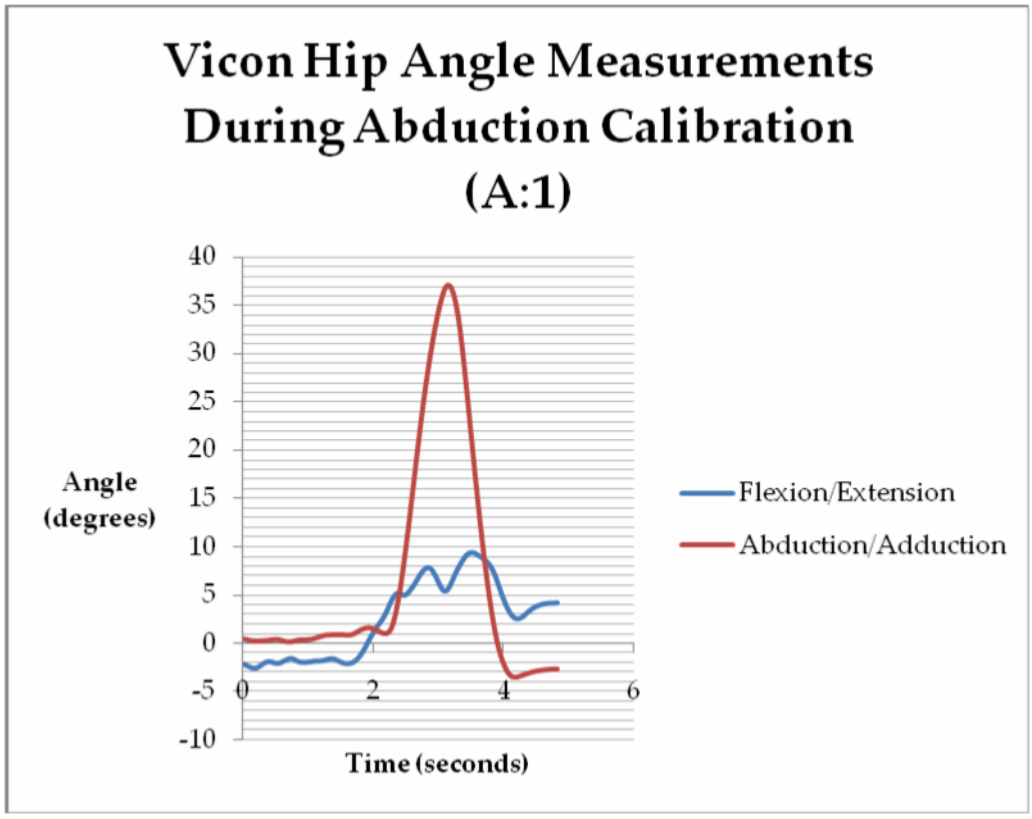

Vicon Hip Angle Measurements During Flexion Calibration (A:2)
120
100
80
60
40
20
0
-20
Angle (degrees)
0
2
4
6
8
Time (seconds)
Flexion/Extension
Abduction/Adduction

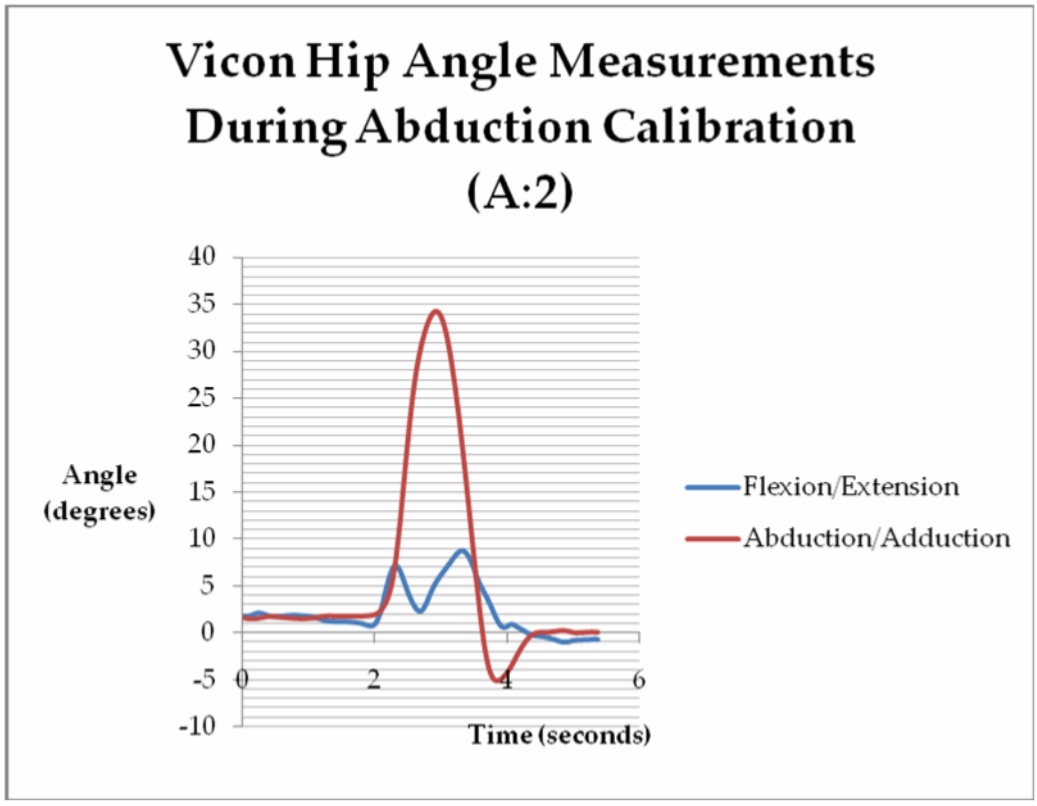

Vicon Hip Angle Measurements During Flexion Calibration (A:3)
120
100
80
60
40
20
0
-20
Angle (degrees)
0
2
4
6
8
Time (seconds)
Flexion/Extension
Abduction/Adduction

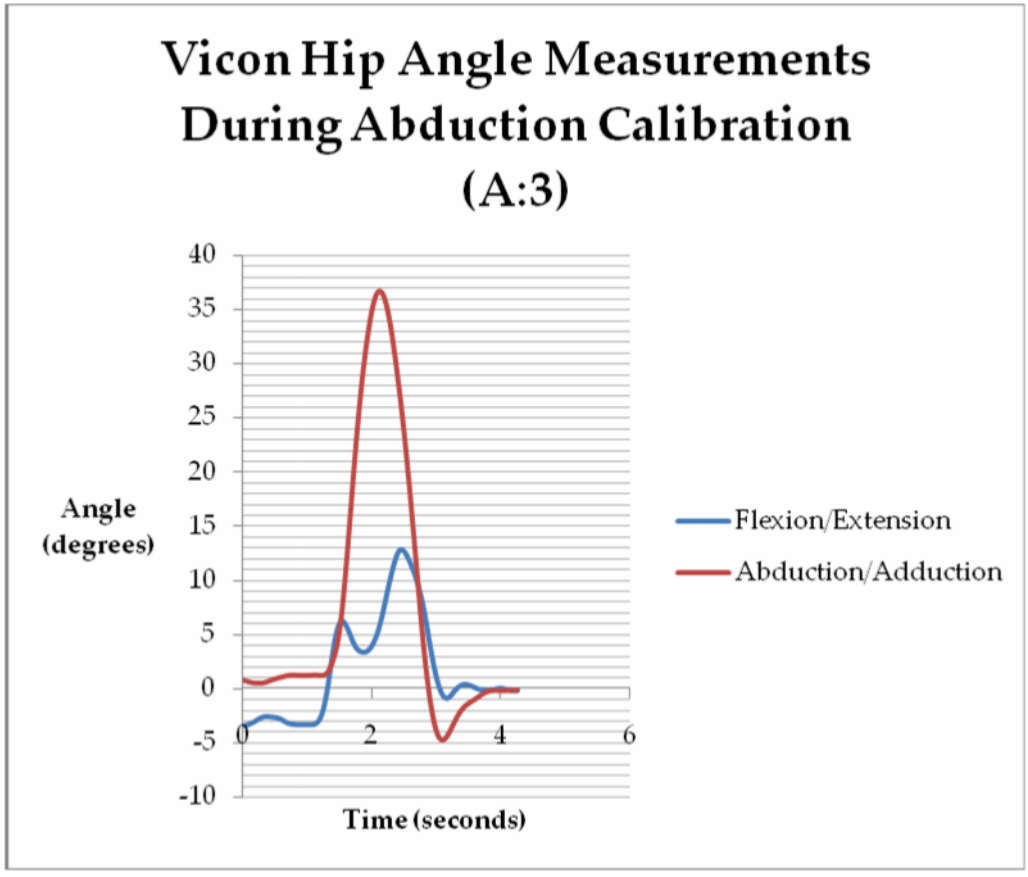

Vicon Hip Angle Measurements During Extension Calibration (A:1)
Angle (degrees)
10
5
0
-5
-10
-15
-20
0
2
4
6
Time (seconds)
Flexion/Extension
Abduction/Adduction

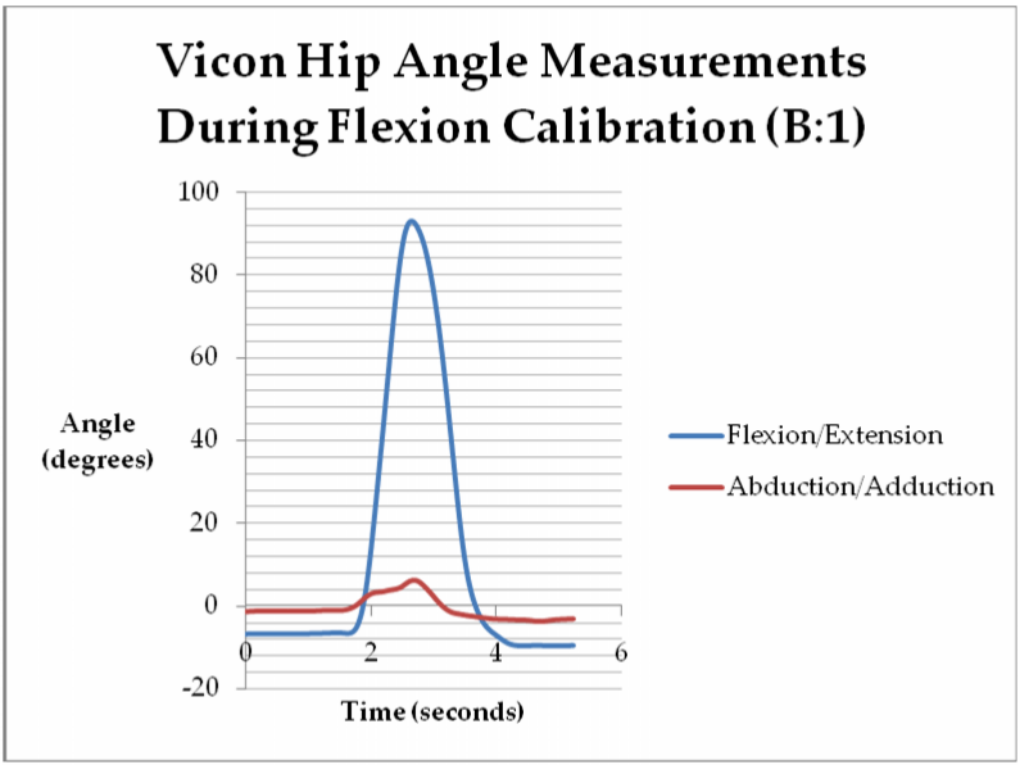

Vicon Hip Angle Measurements During Extension Calibration (A:2)
Angle (degrees)
10
5
0
-5
-10
-15
-20
0
2
4
6
Time (seconds)
Flexion/Extension
Abduction/Adduction

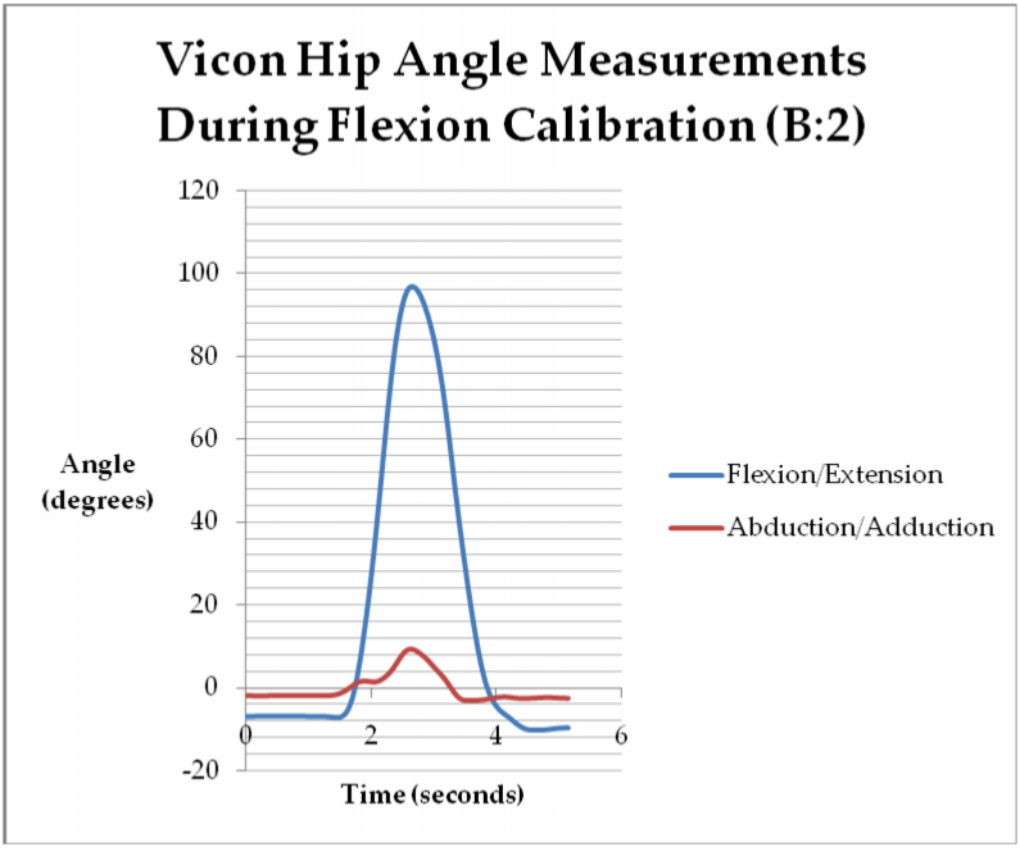

Vicon Hip Angle Measurements During Extension Calibration (A:3)
Angle (degrees)
20
15
10
5
0
-5
-10
-15
-20
0
2
4
6
Time (seconds)
Flexion/Extension
Abduction/Adduction

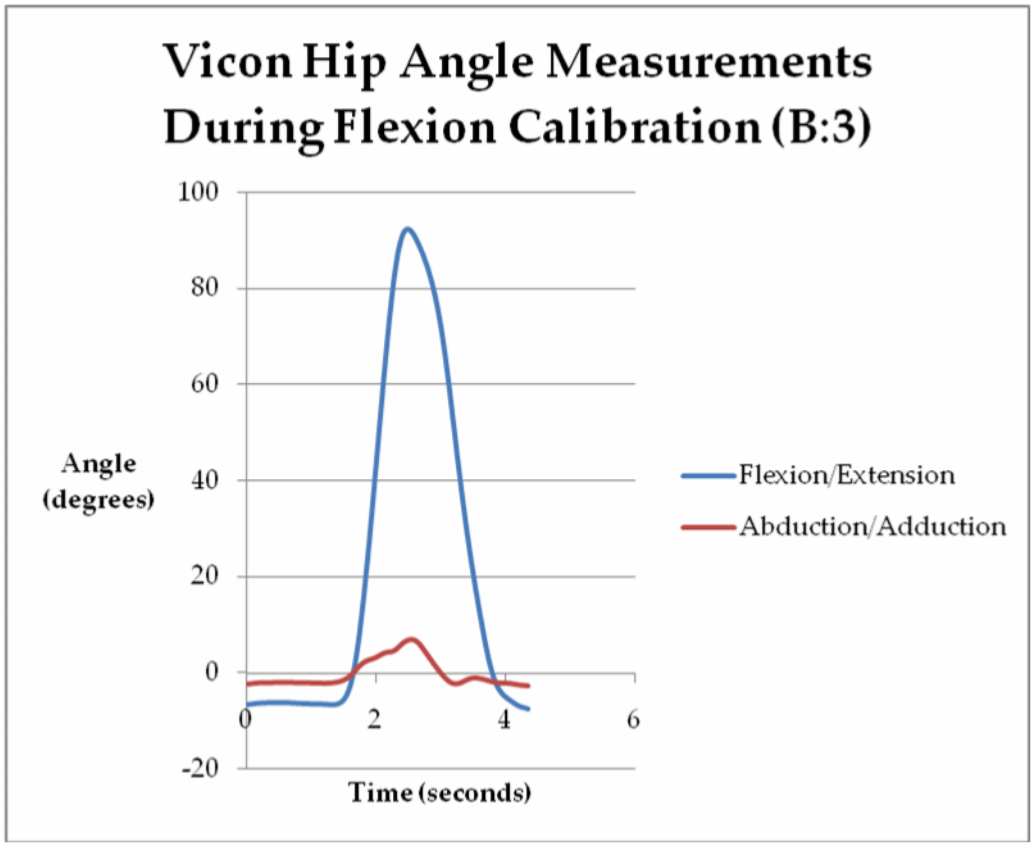

Vicon Hip Angle Measurements During Abduction Calibration (A:1)
Angle (degrees)
40
35
30
25
20
15
10
5
0
-5
-10
0
2
4
6
Time (seconds)
Flexion/Extension
Abduction/Adduction

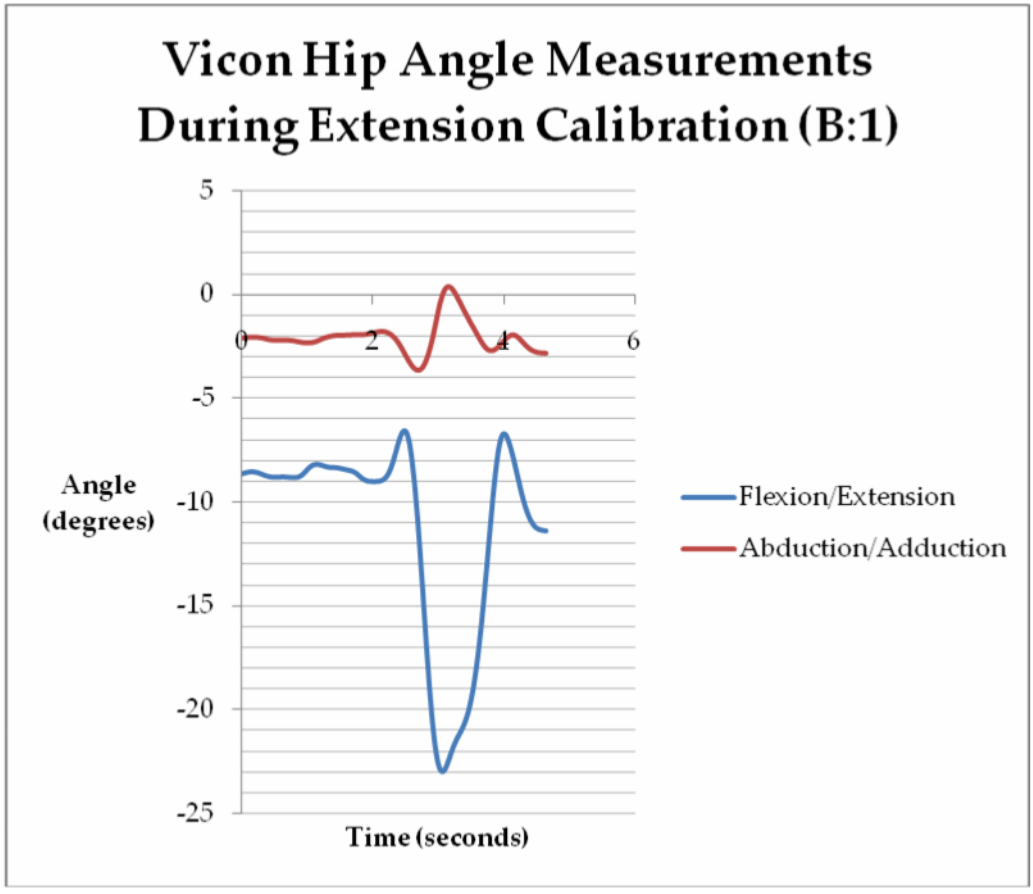

Vicon Hip Angle Measurements During Abduction Calibration (A:2)
Angle (degrees)
40
35
30
25
20
15
10
5
0
-5
-10
0
2
4
6
Time (seconds)
Flexion/Extension
Abduction/Adduction

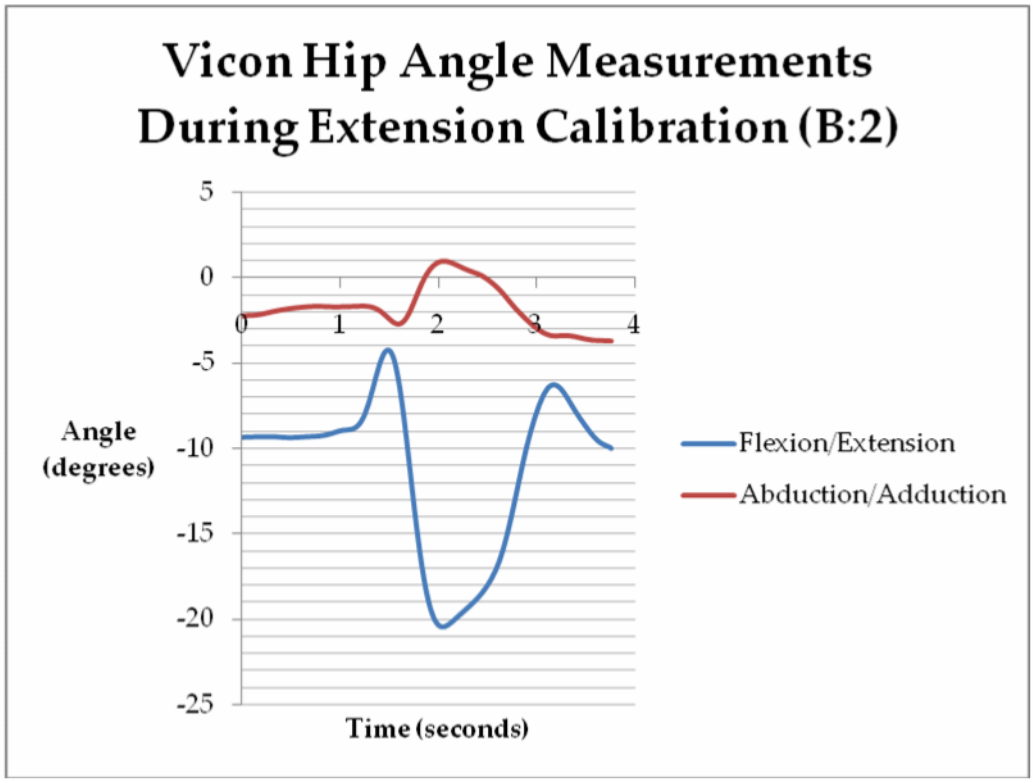

Vicon Hip Angle Measurements During Abduction Calibration (A:3)
Angle (degrees)
40
35
30
25
20
15
10
5
0
-5
-10
0
2
4
6
Time (seconds)
Flexion/Extension
Abduction/Adduction

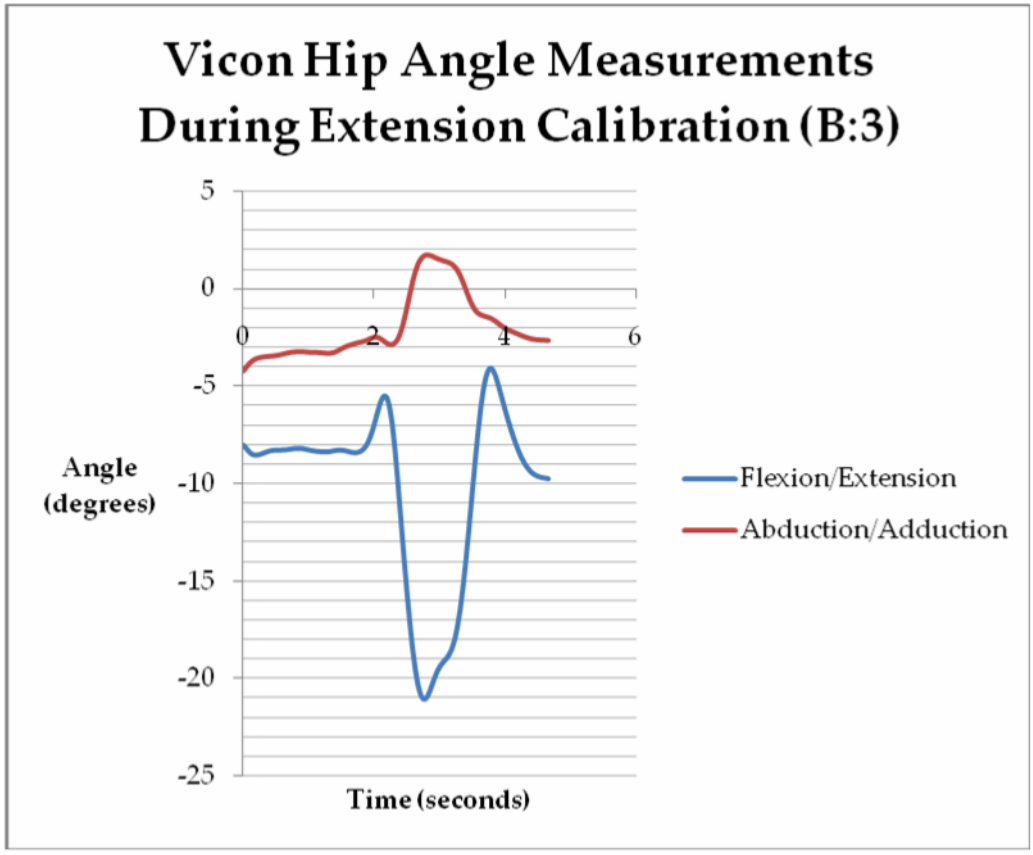

Vicon Hip Angle Measurements During Flexion Calibration (B:1)
100
80
60
40
20
0
-20
0
2
4
6
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

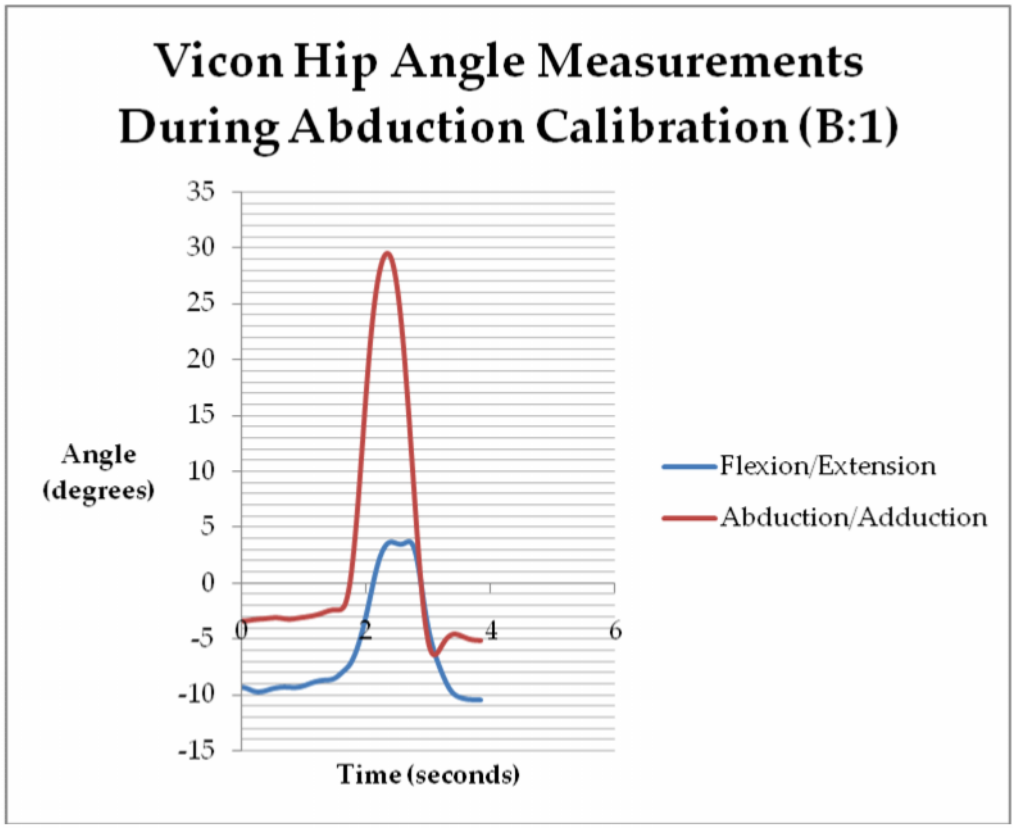

Vicon Hip Angle Measurements During Flexion Calibration (B:2)
120
100
80
60
40
20
0
-20
0
2
4
6
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

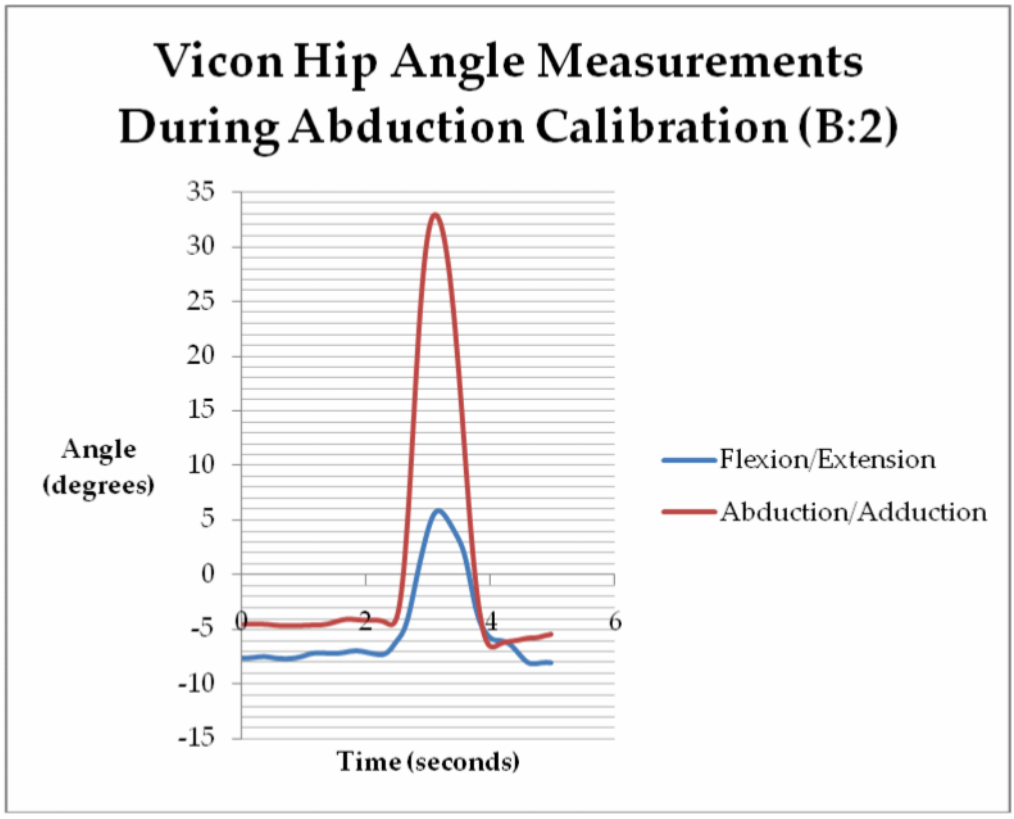

Vicon Hip Angle Measurements During Flexion Calibration (B:3)
100
80
60
40
20
0
-20
Angle (degrees)
0
2
4
6
Time (seconds)
Flexion/Extension
Abduction/Adduction

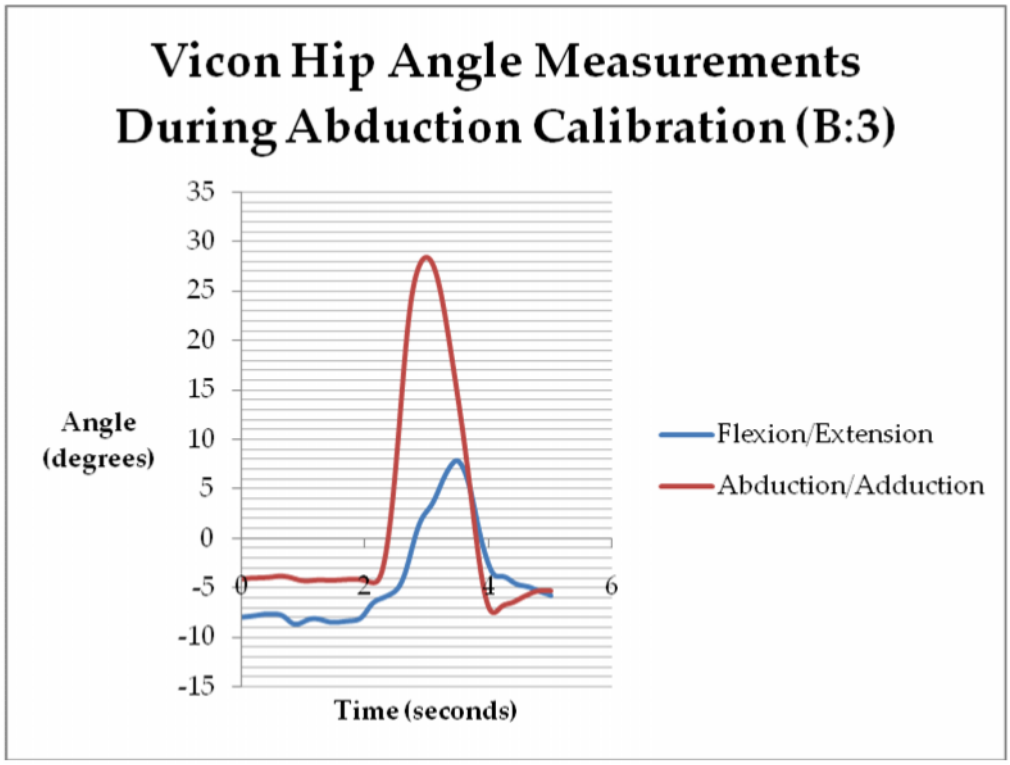

Vicon Hip Angle Measurements During Extension Calibration (B:1)
5
0
-5
-10
-15
-20
-25
Angle (degrees)
0
2
4
6
Time (seconds)
Flexion/Extension
Abduction/Adduction

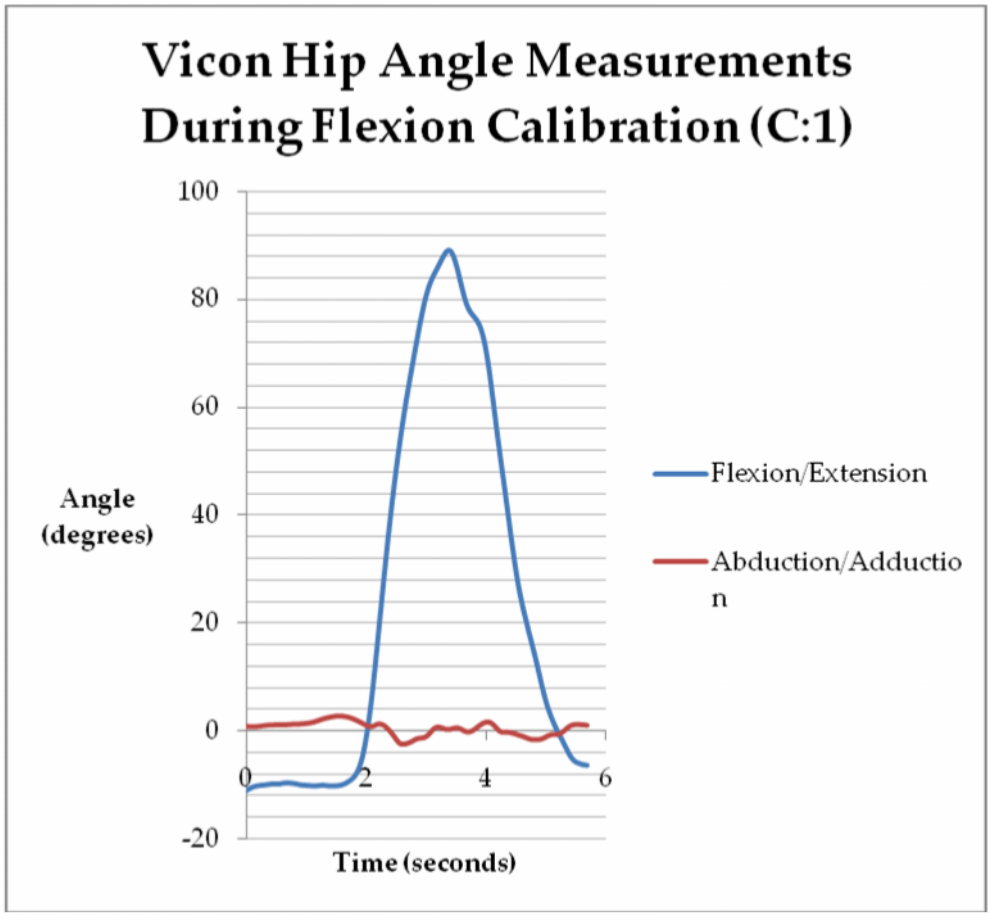

Vicon Hip Angle Measurements During Extension Calibration (B:2)
5
0
-5
-10
-15
-20
-25
0
1
2
3
4
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

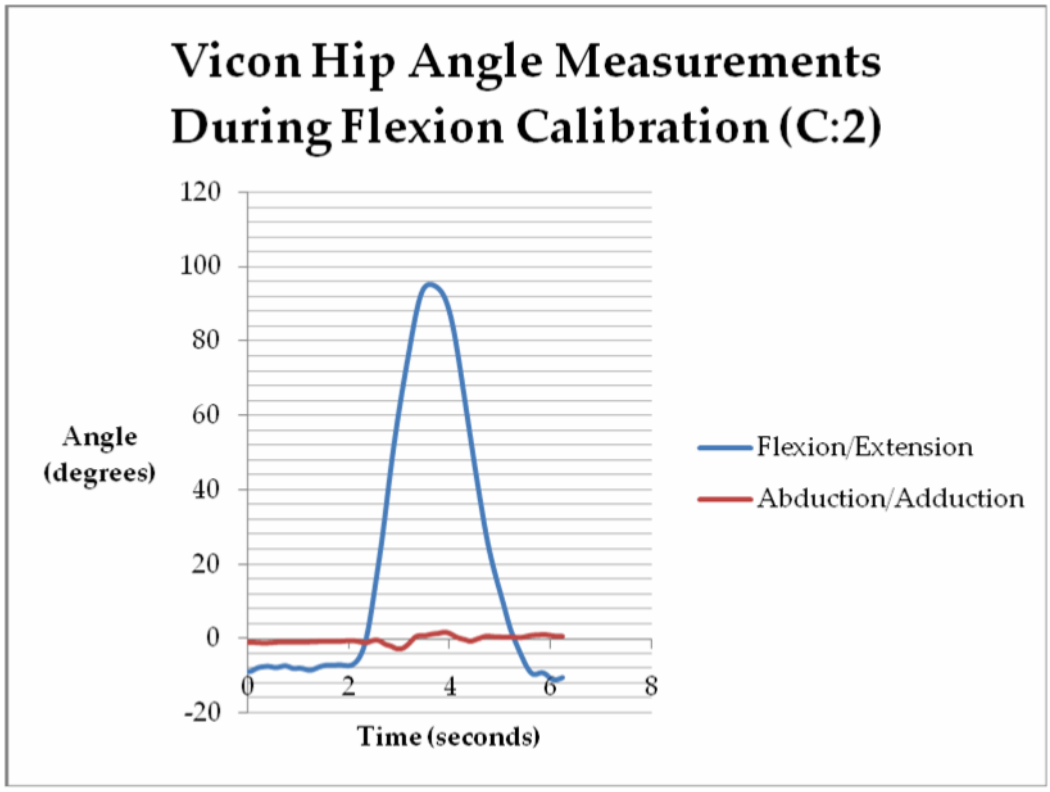

Vicon Hip Angle Measurements During Extension Calibration (B:3)
5
0
-5
-10
-15
-20
-25
0
2
4
6
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

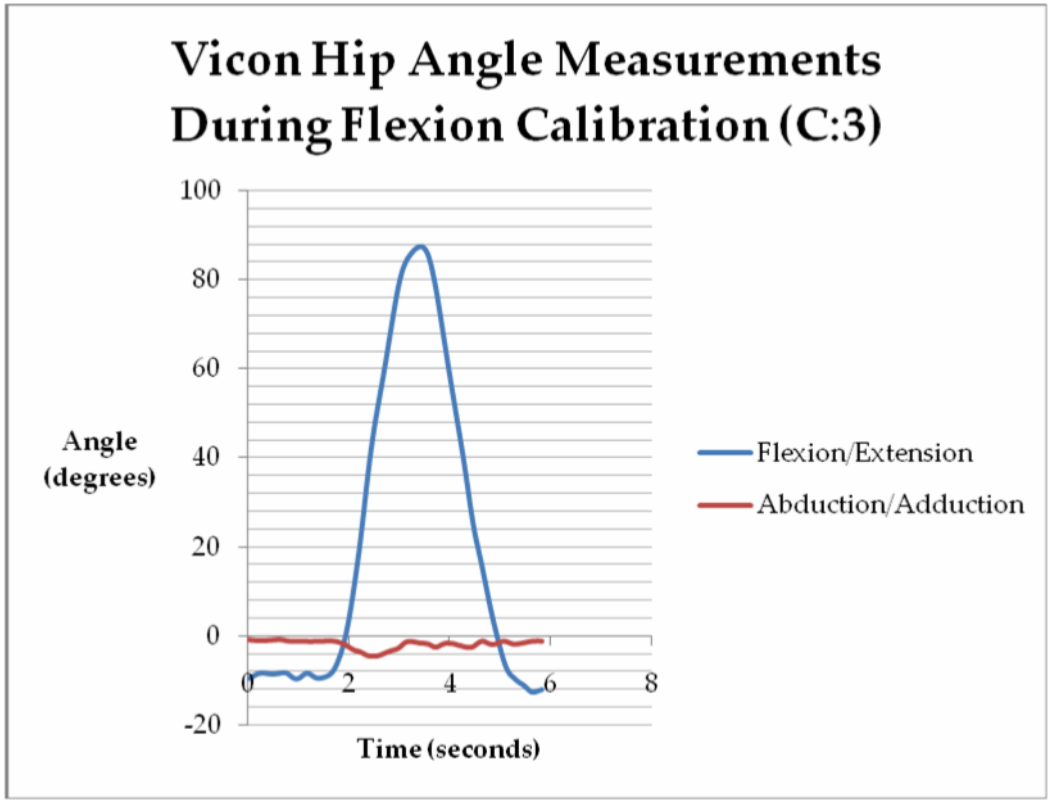

Vicon Hip Angle Measurements During Abduction Calibration (B:1)
35
30
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

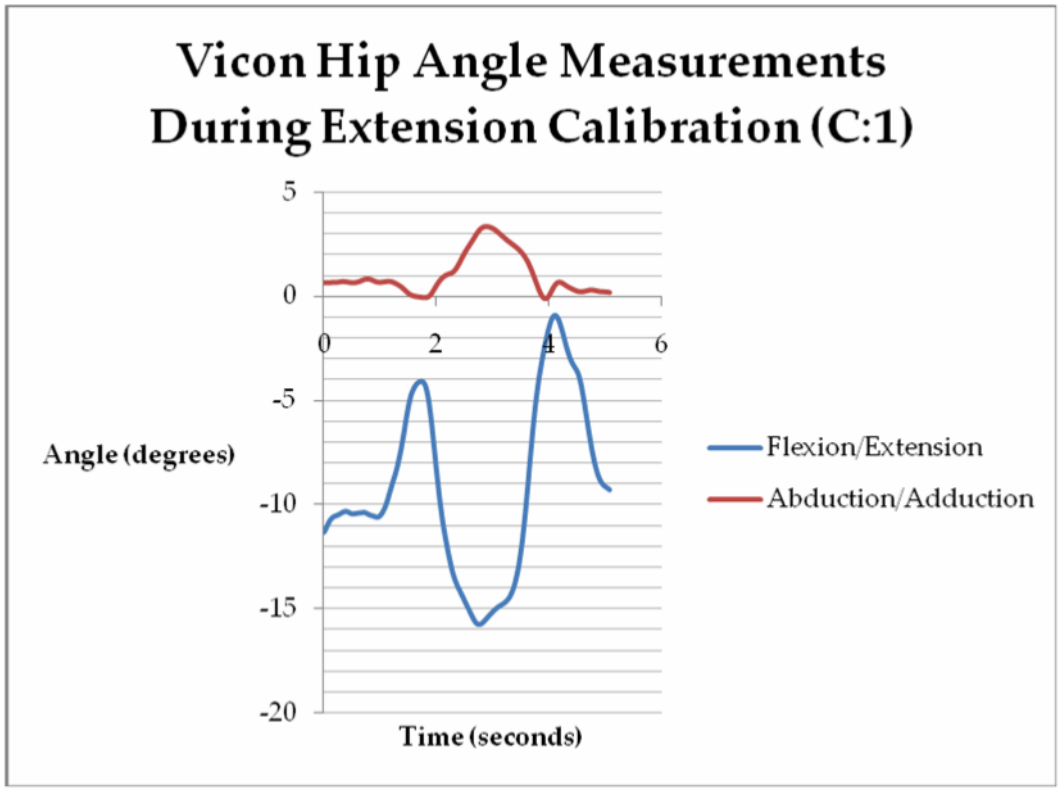

Vicon Hip Angle Measurements During Abduction Calibration (B:2)
35
30
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

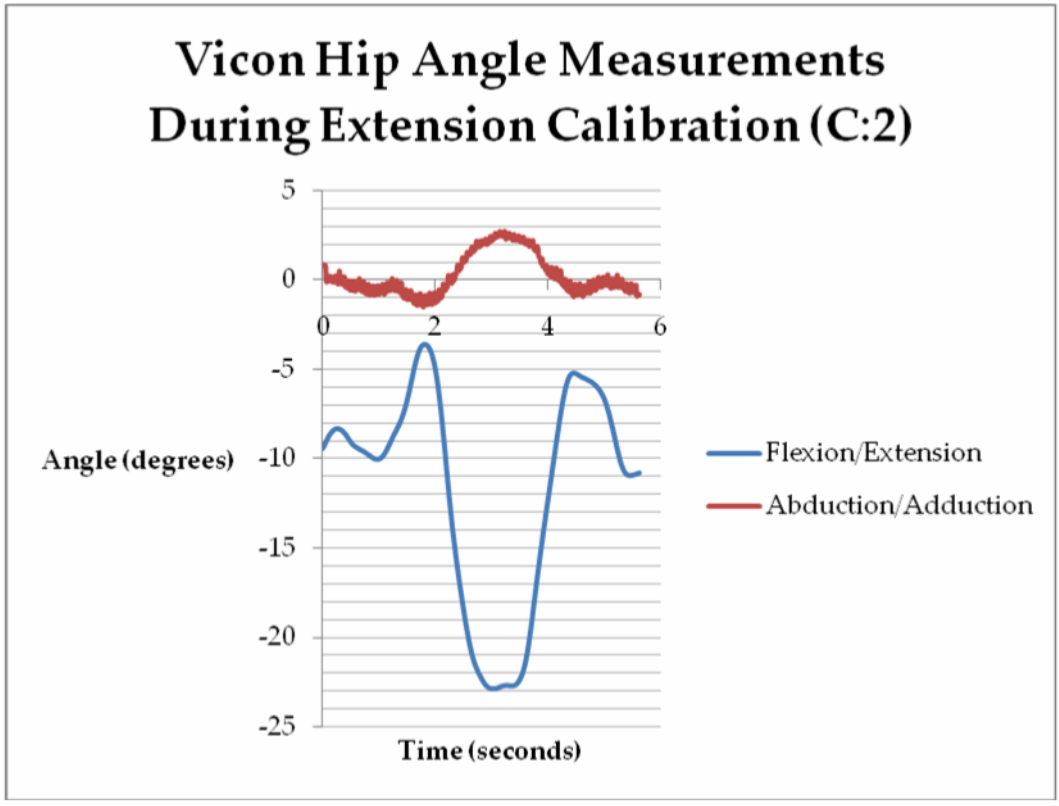

Vicon Hip Angle Measurements During Abduction Calibration (B:3)
35
30
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

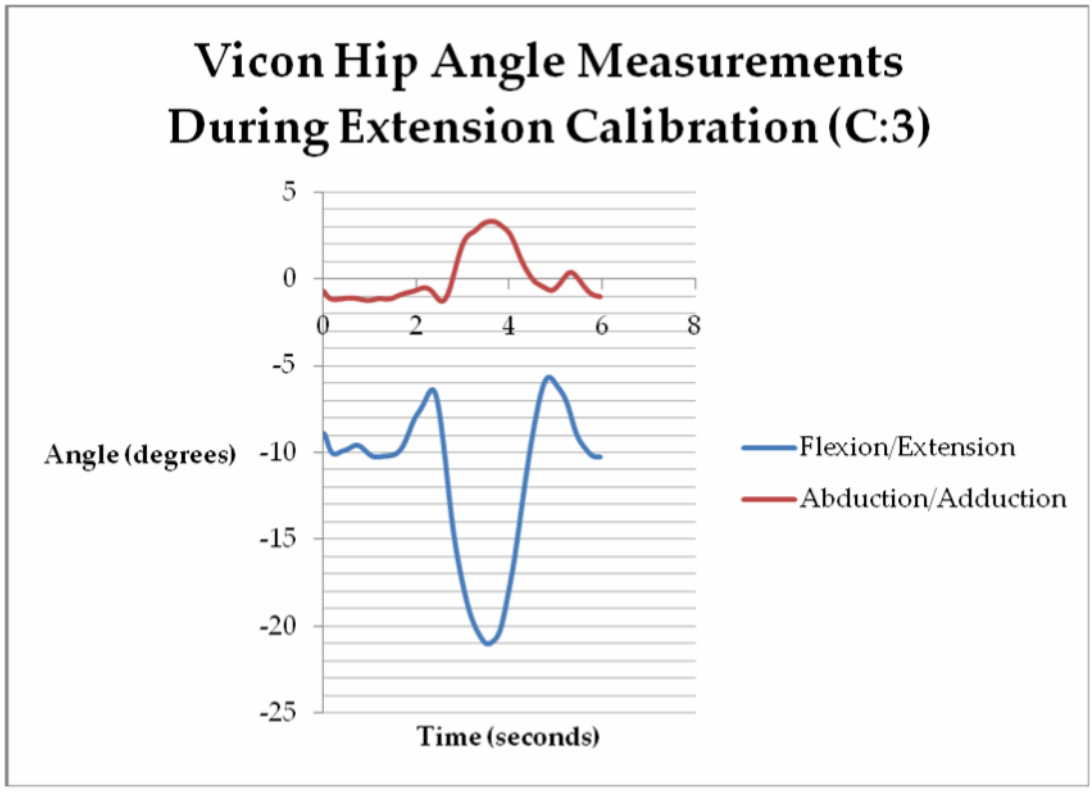

Vicon Hip Angle Measurements During Flexion Calibration (C:1)
100
80
60
40
20
0
-20
0
2
4
6
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

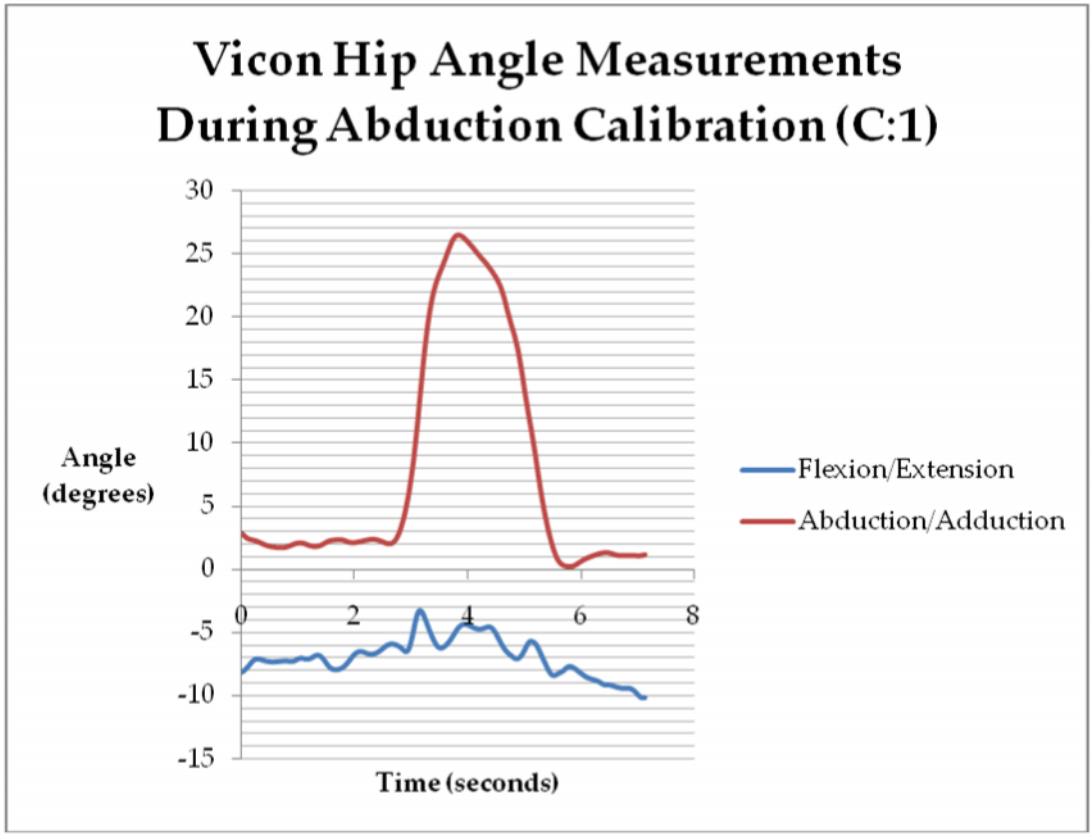

Vicon Hip Angle Measurements During Flexion Calibration (C:2)
120
100
80
60
40
20
0
-20
Angle (degrees)
0
2
4
6
8
Time (seconds)
Flexion/Extension
Abduction/Adduction

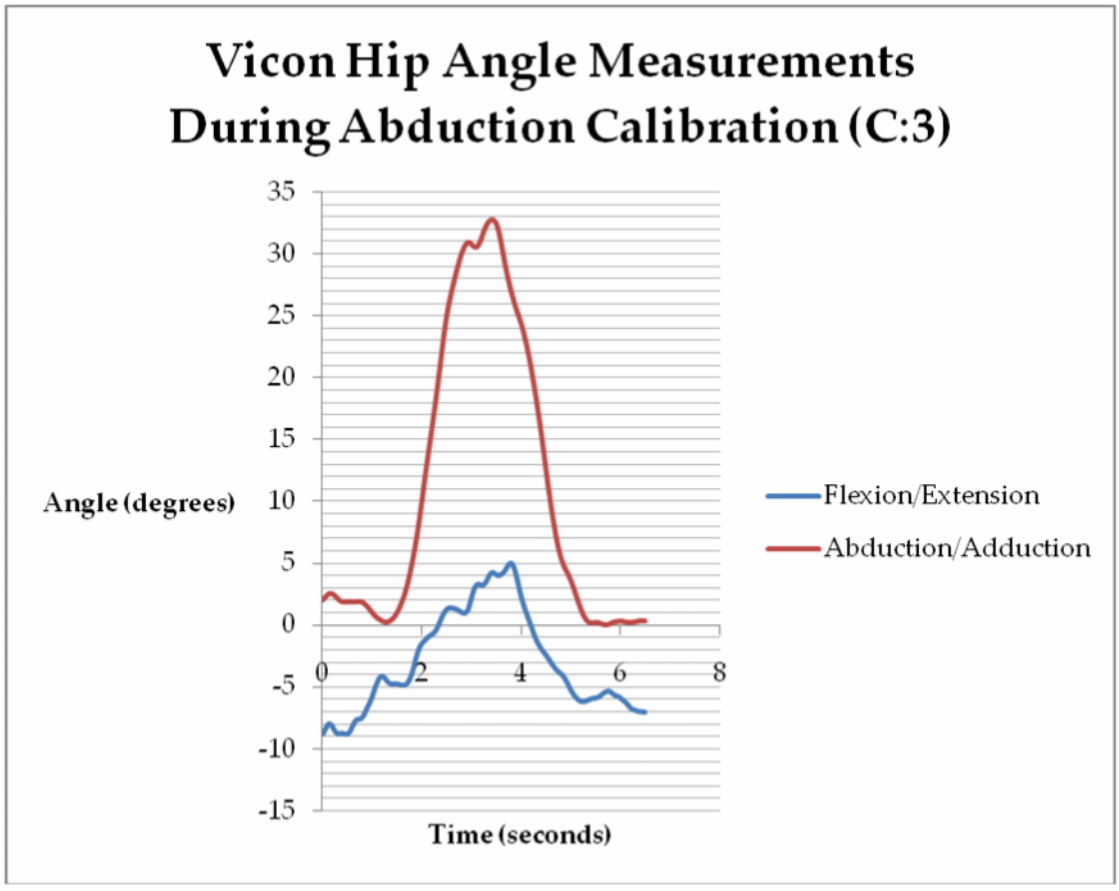

Vicon Hip Angle Measurements During Flexion Calibration (C:3)
100
80
60
40
20
0
-20
Angle (degrees)
0
2
4
6
8
Time (seconds)
Flexion/Extension
Abduction/Adduction


Vicon Hip Angle Measurements During Extension Calibration (C:1)
5
0
-5
-10
-15
-20
0
2
4
6
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

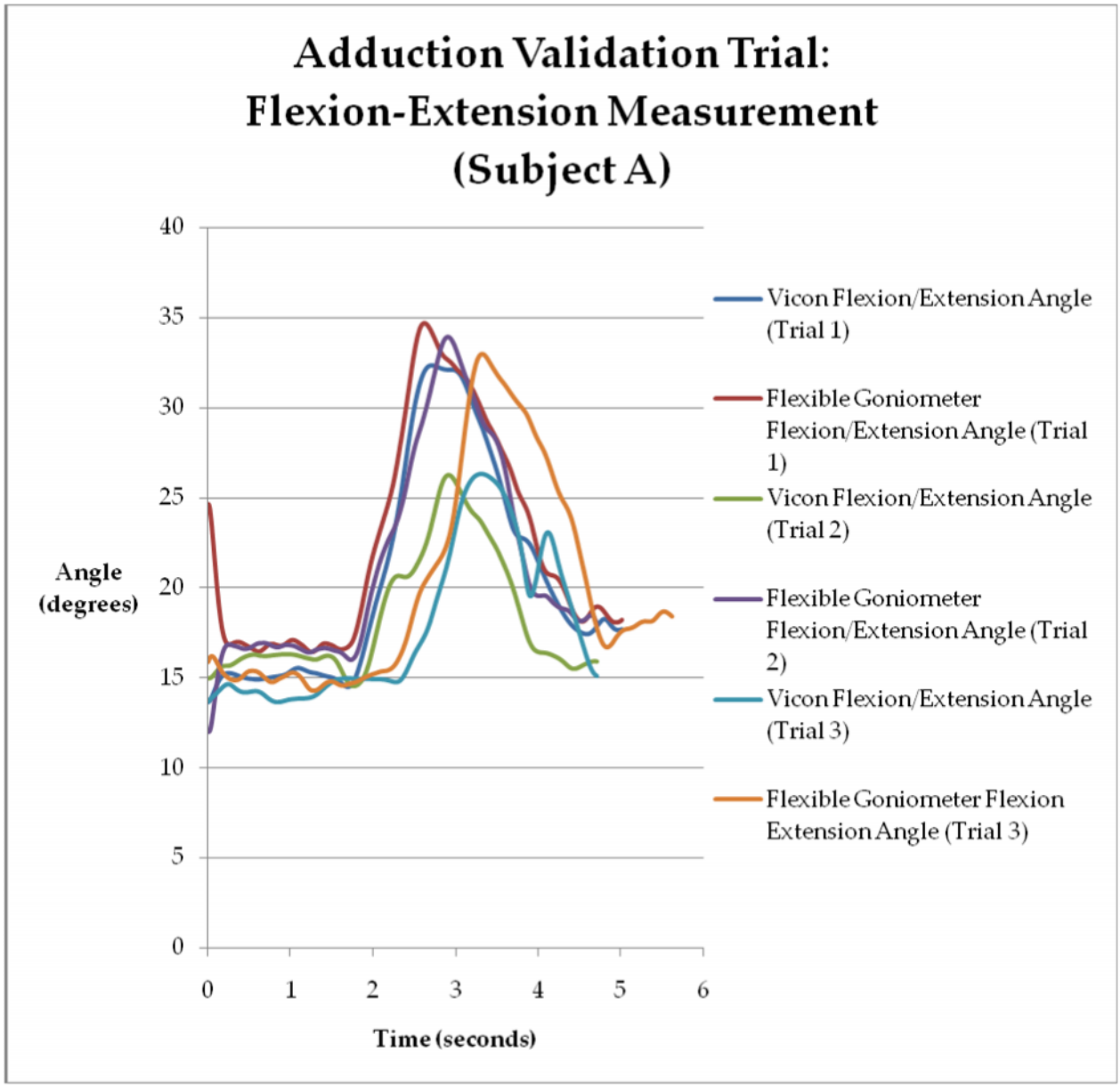

Vicon Hip Angle Measurements During Extension Calibration (C:2)
5
0
-5
-10
-15
-20
-25
0
2
4
6
Angle (degrees)
Time (seconds)
Flexion/Extension
Abduction/Adduction

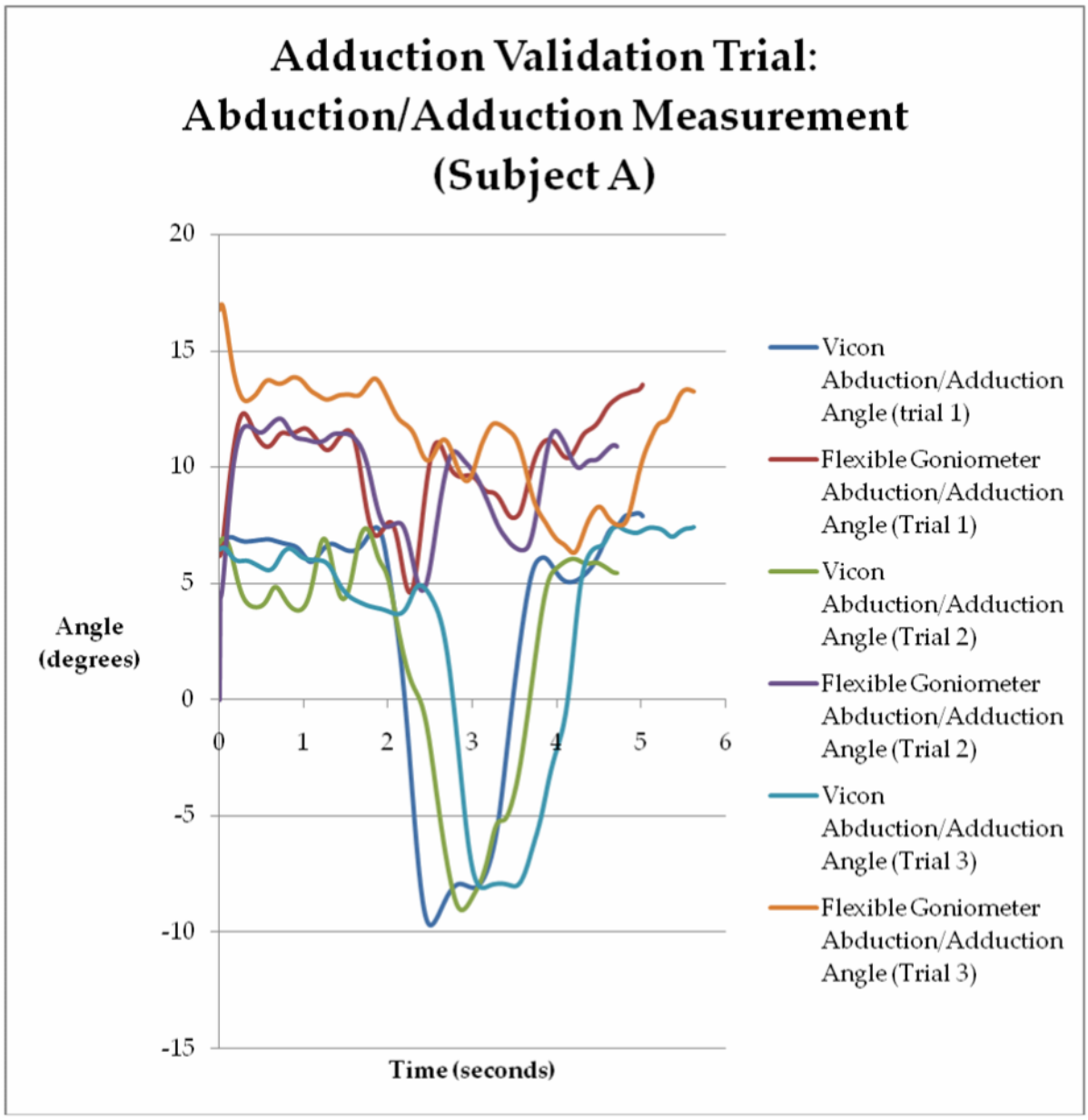

Vicon Hip Angle Measurements
During Extension Calibration (C:3)
Angle (degrees)
5
0
-5
-10
-15
-20
-25
0
2
4
6
8
Time (seconds)
Flexion/Extension
Abduction/Adduction

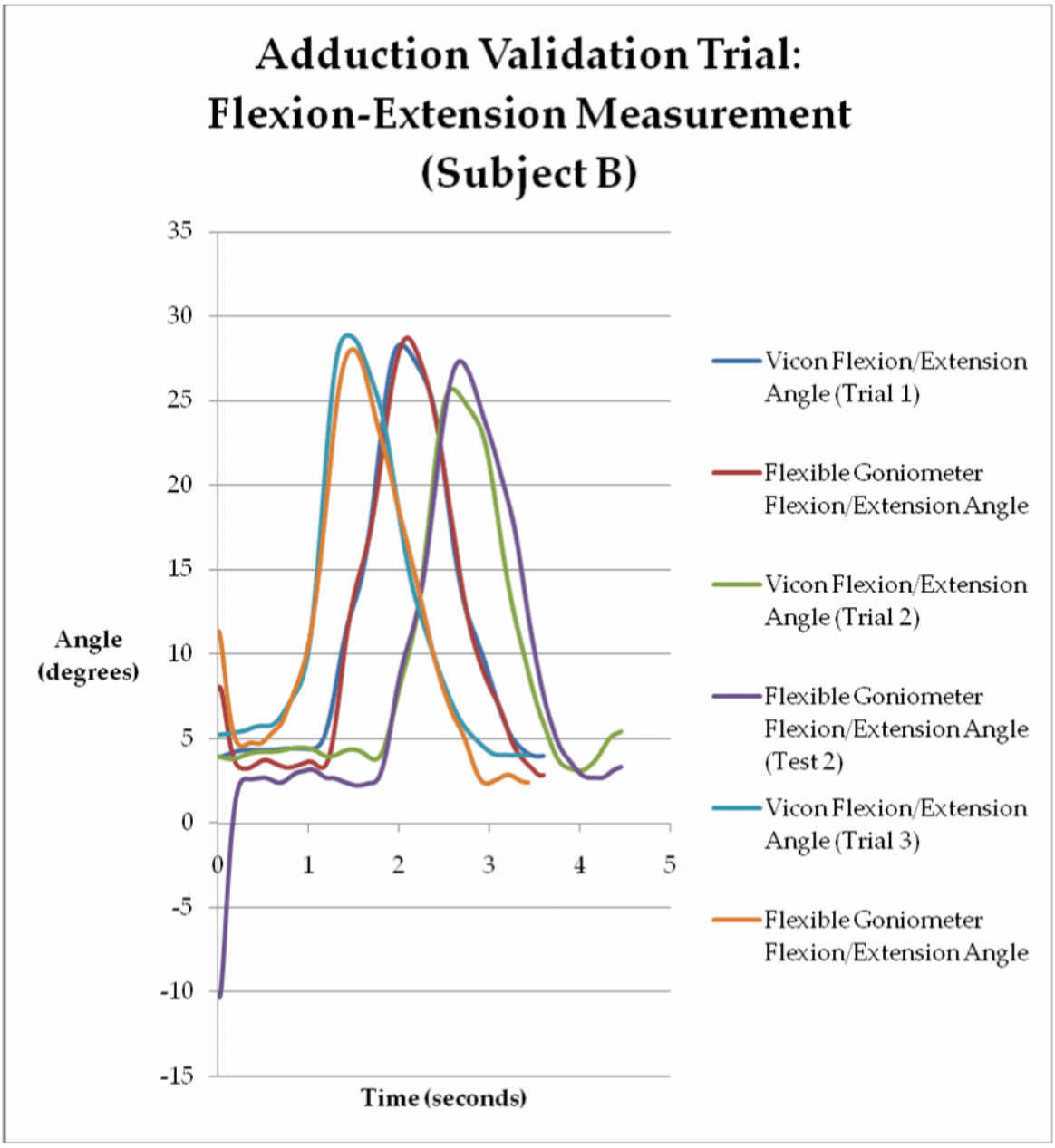

Vicon Hip Angle Measurements
During Abduction Calibration (C:1)
Angle
(degrees)
30
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
Time (seconds)
Flexion/Extension
Abduction/Adduction

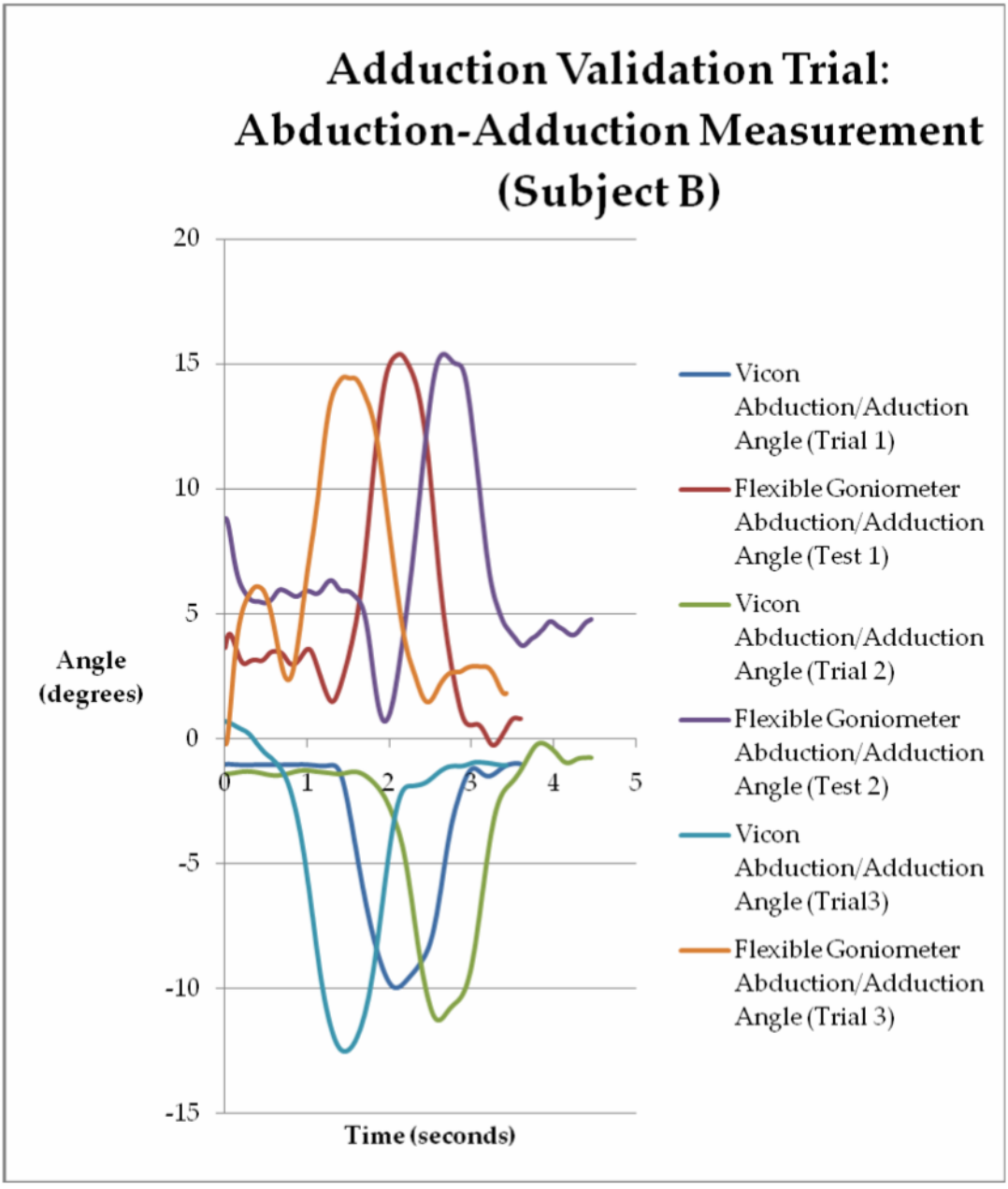

Vicon Hip Angle Measurements During Abduction Calibration (C:3)
Angle (degrees)
35
30
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
Time (seconds)
Flexion/Extension
Abduction/Adduction

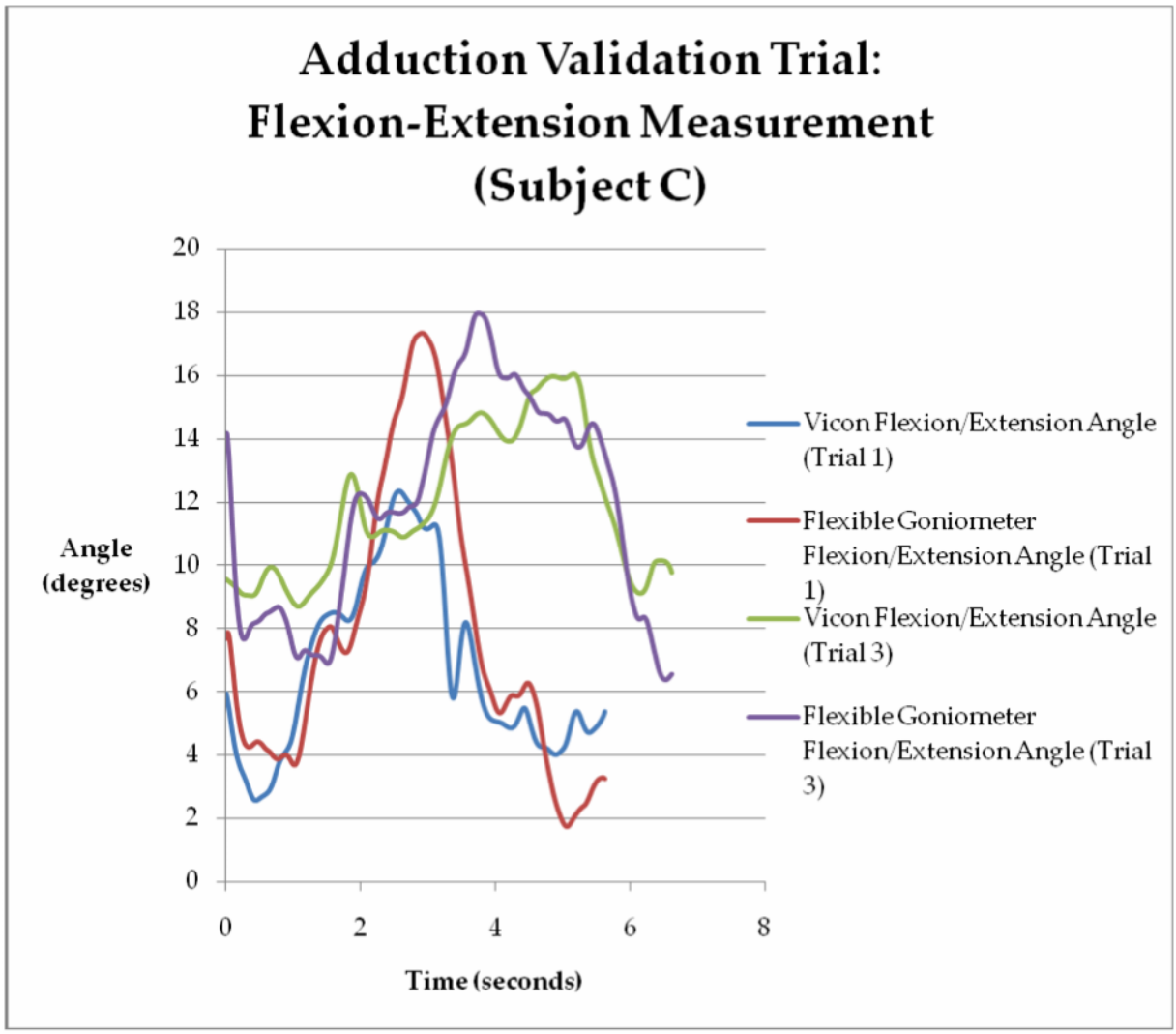
Appendix C:
ADDUCTION TRIAL RESULTS

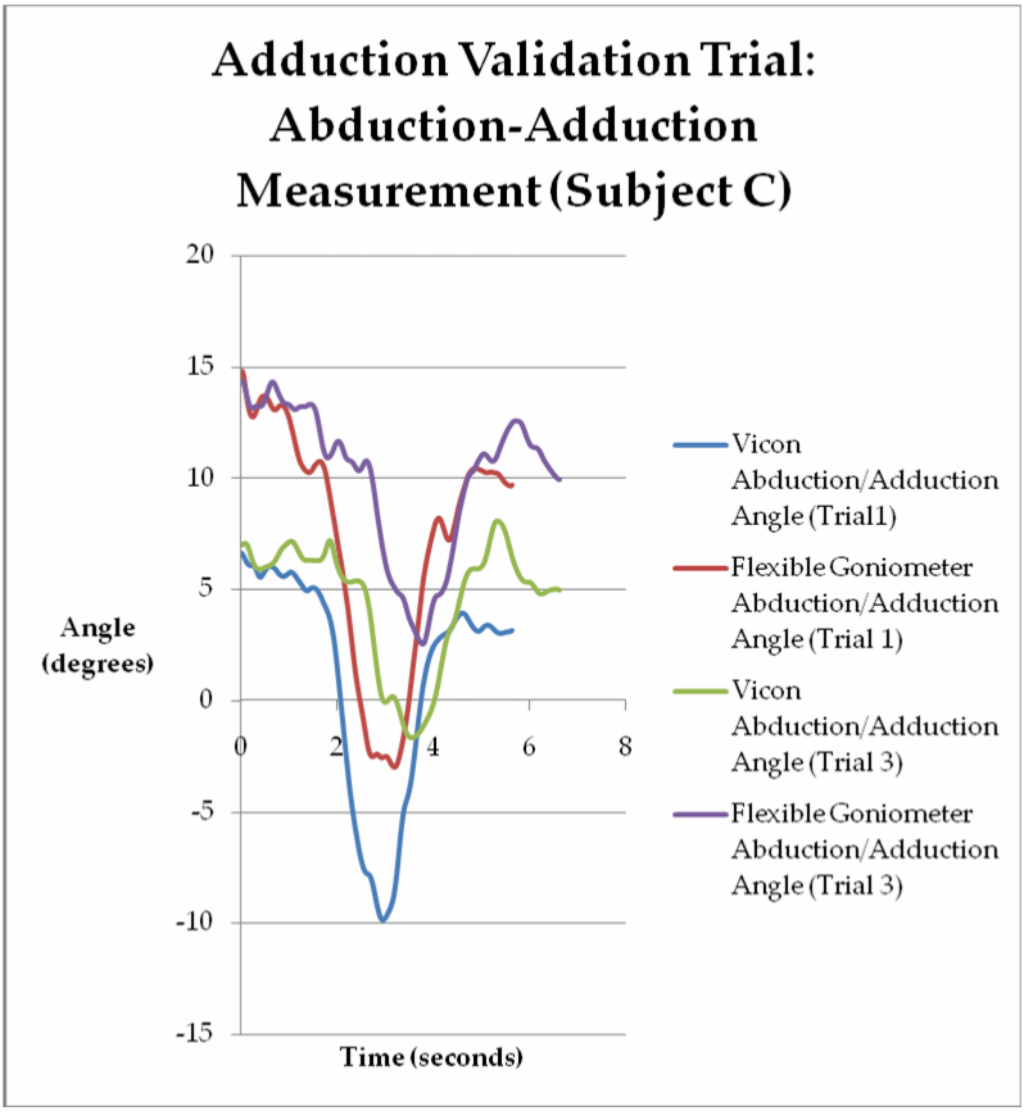

Adduction Validation Trial:
Flexion-Extension Measurement
(Subject A)
Angle (degrees)
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
Time (seconds)
Vicon Flexion/Extension Angle (Trial 1)
Flexible Goniometer Flexion/Extension Angle (Trial 1)
Vicon Flexion/Extension Angle (Trial 2)
Flexible Goniometer Flexion/Extension Angle (Trial 2)
Vicon Flexion/Extension Angle (Trial 3)
Flexible Goniometer Flexion Extension Angle (Trial 3)


Adduction Validation Trial: Abduction/Adduction Measurement (Subject A)
Angle (degrees)
20
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
6
Time (seconds)
Vicon Abduction/Adduction Angle (trial 1)
Flexible Goniometer Abduction/Adduction Angle (Trial 1)
Vicon Abduction/Adduction Angle (Trial 2)
Flexible Goniometer Abduction/Adduction Angle (Trial 2)
Vicon Abduction/Adduction Angle (Trial 3)
Flexible Goniometer Abduction/Adduction Angle (Trial 3)

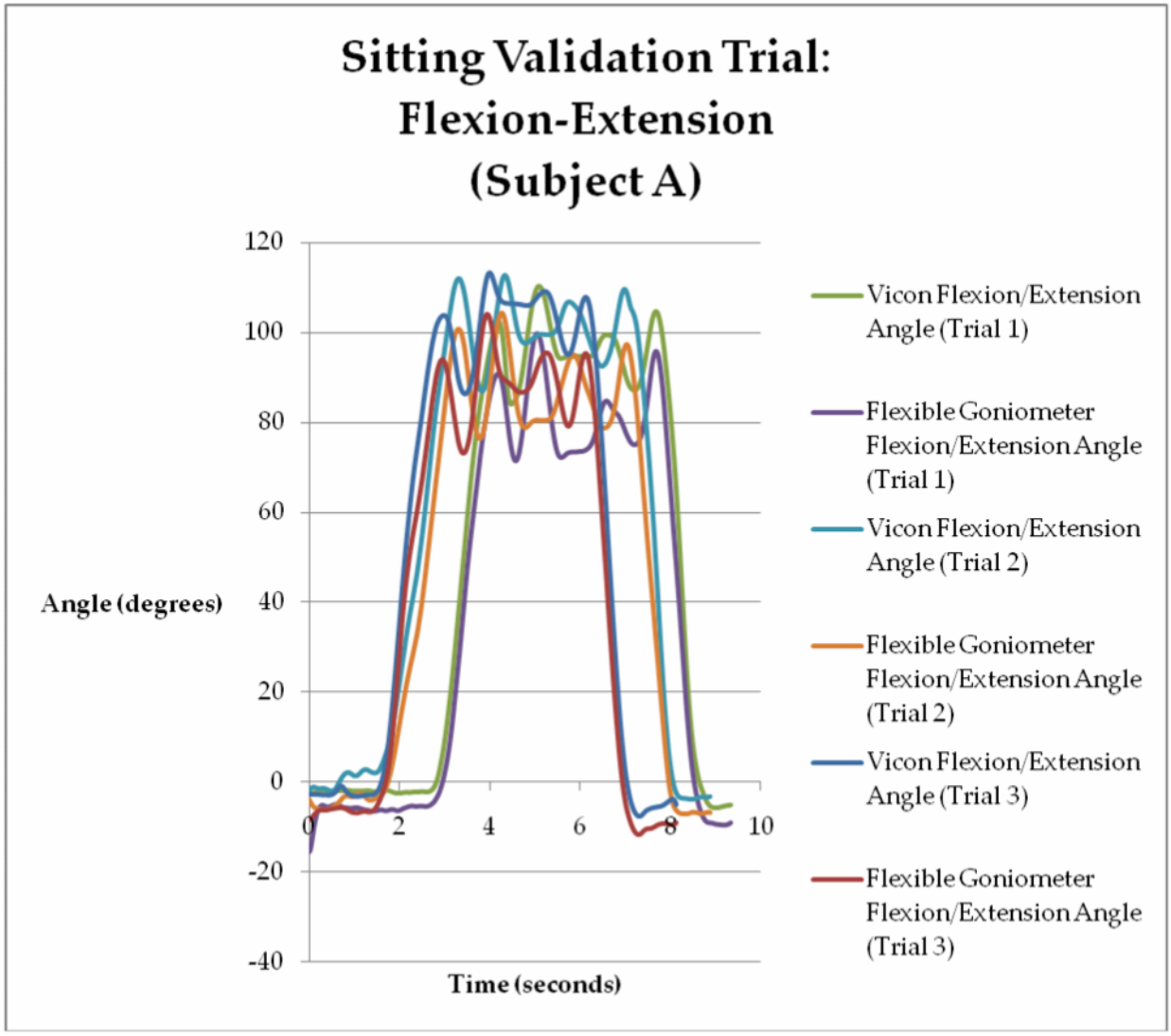

Adduction Validation Trial:
Flexion-Extension Measurement
(Subject B)
Angle (degrees)
35
30
25
20
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
Time (seconds)
Vicon Flexion/Extension Angle (Trial 1)
Flexible Goniometer Flexion/Extension Angle
Vicon Flexion/Extension Angle (Trial 2)
Flexible Goniometer Flexion/Extension Angle (Test 2)
Vicon Flexion/Extension Angle (Trial 3)
Flexible Goniometer Flexion/Extension Angle

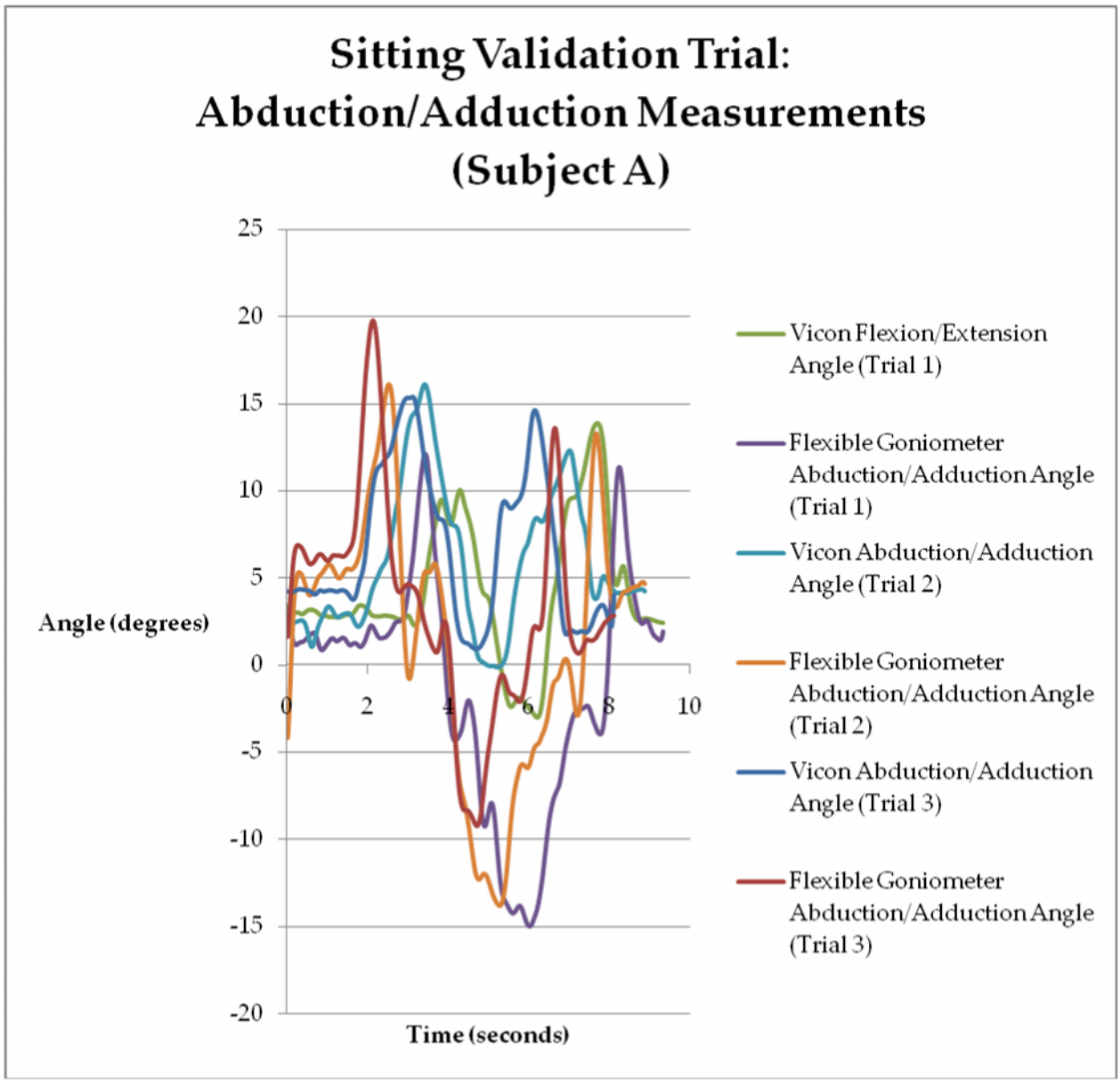

Adduction Validation Trial: Abduction-Adduction Measurement (Subject B)
Angle (degrees)
20
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
Time (seconds)
Vicon Abduction/Aduction Angle (Trial 1)
Flexible Goniometer Abduction/Adduction Angle (Test 1)
Vicon Abduction/Adduction Angle (Trial 2)
Flexible Goniometer Abduction/Adduction Angle (Test 2)
Vicon Abduction/Adduction Angle (Trial3)
Flexible Goniometer Abduction/Adduction Angle (Trial 3)

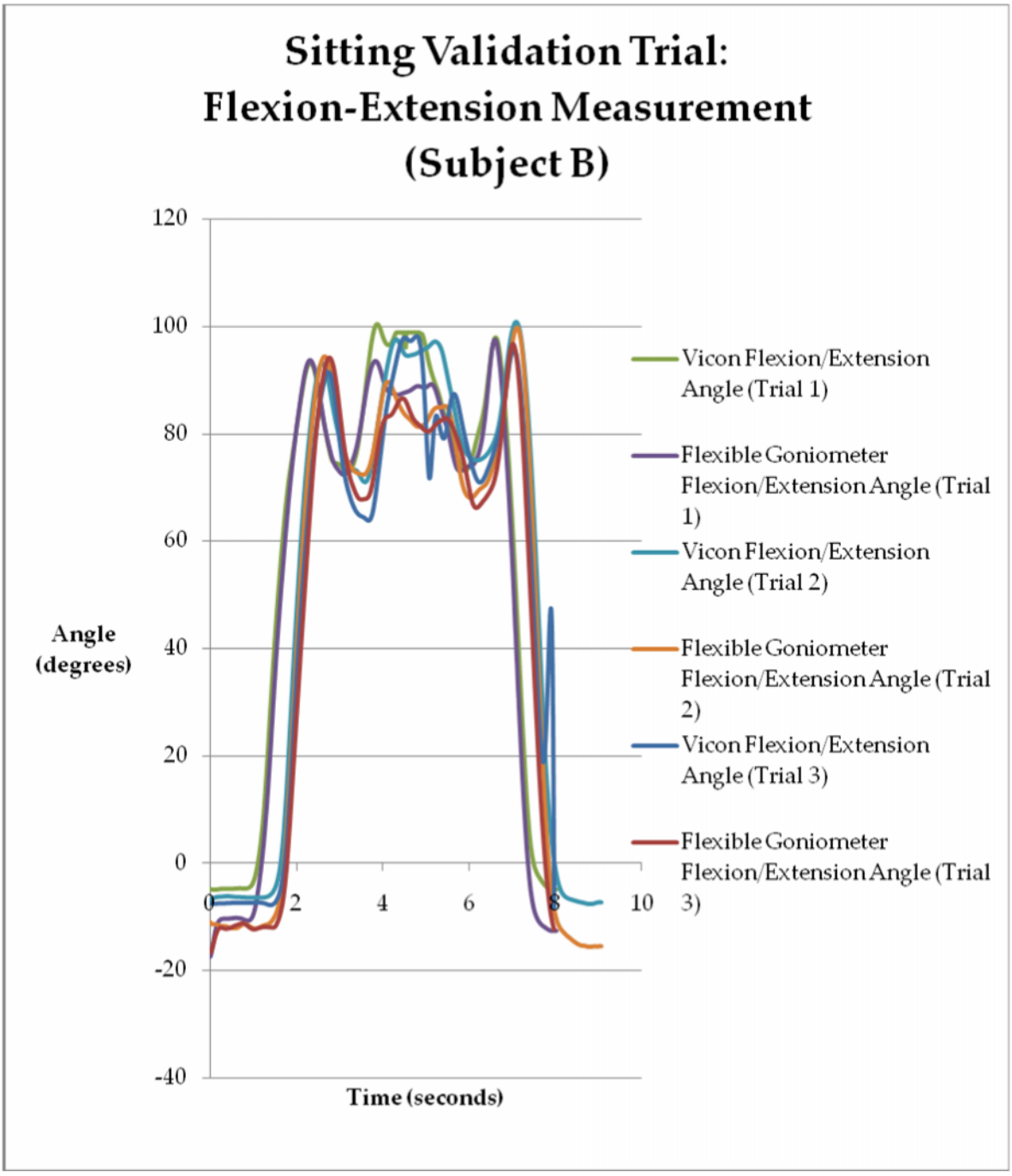

Adduction Validation Trial:
Flexion-Extension Measurement
(Subject C)
Angle (degrees)
20
18
16
14
12
10
8
6
4
2
0
0
2
4
6
8
Time (seconds)
Vicon Flexion/Extension Angle (Trial 1)
Flexible Goniometer Flexion/Extension Angle (Trial 1)
Vicon Flexion/Extension Angle (Trial 3)
Flexible Goniometer Flexion/Extension Angle (Trial 3)

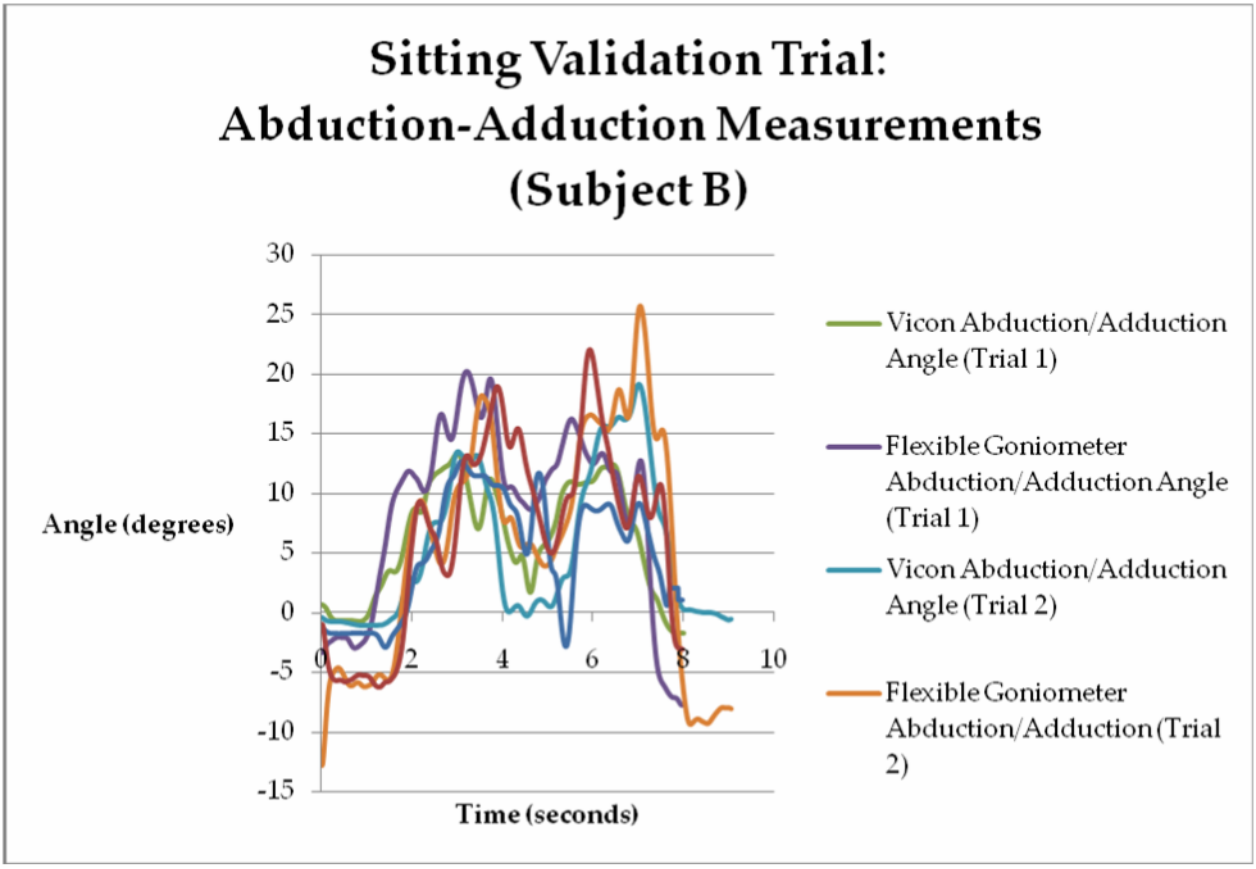

Adduction Validation Trial: Abduction-Adduction Measurement (Subject C)
Angle (degrees)
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
Time (seconds)
Vicon Abduction/Adduction Angle (Trial1)
Flexible Goniometer Abduction/Adduction Angle (Trial 1)
Vicon Abduction/Adduction Angle (Trial 3)
Flexible Goniometer Abduction/Adduction Angle (Trial 3)

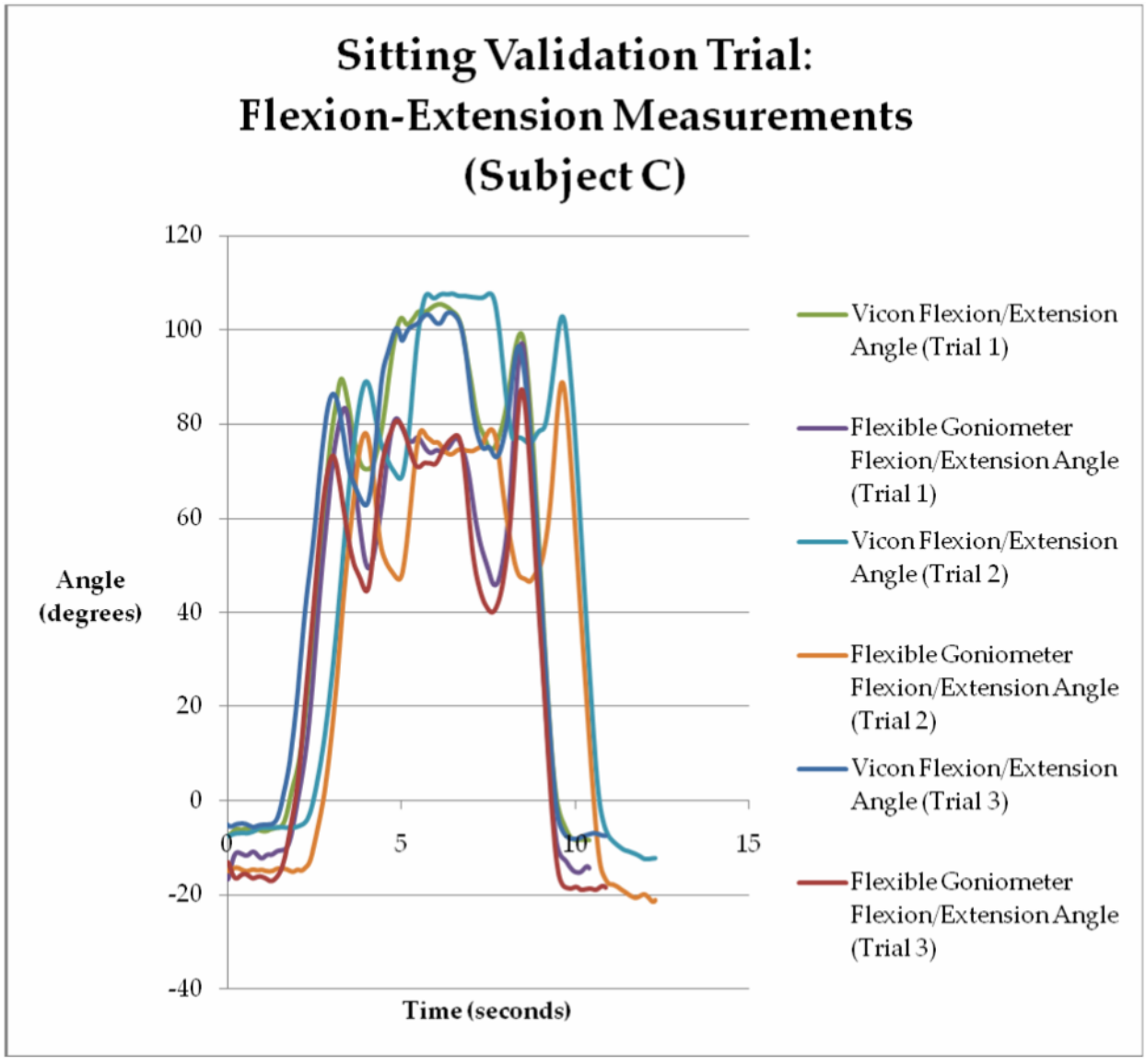
Appendix D:
SITTING TRIAL RESULTS

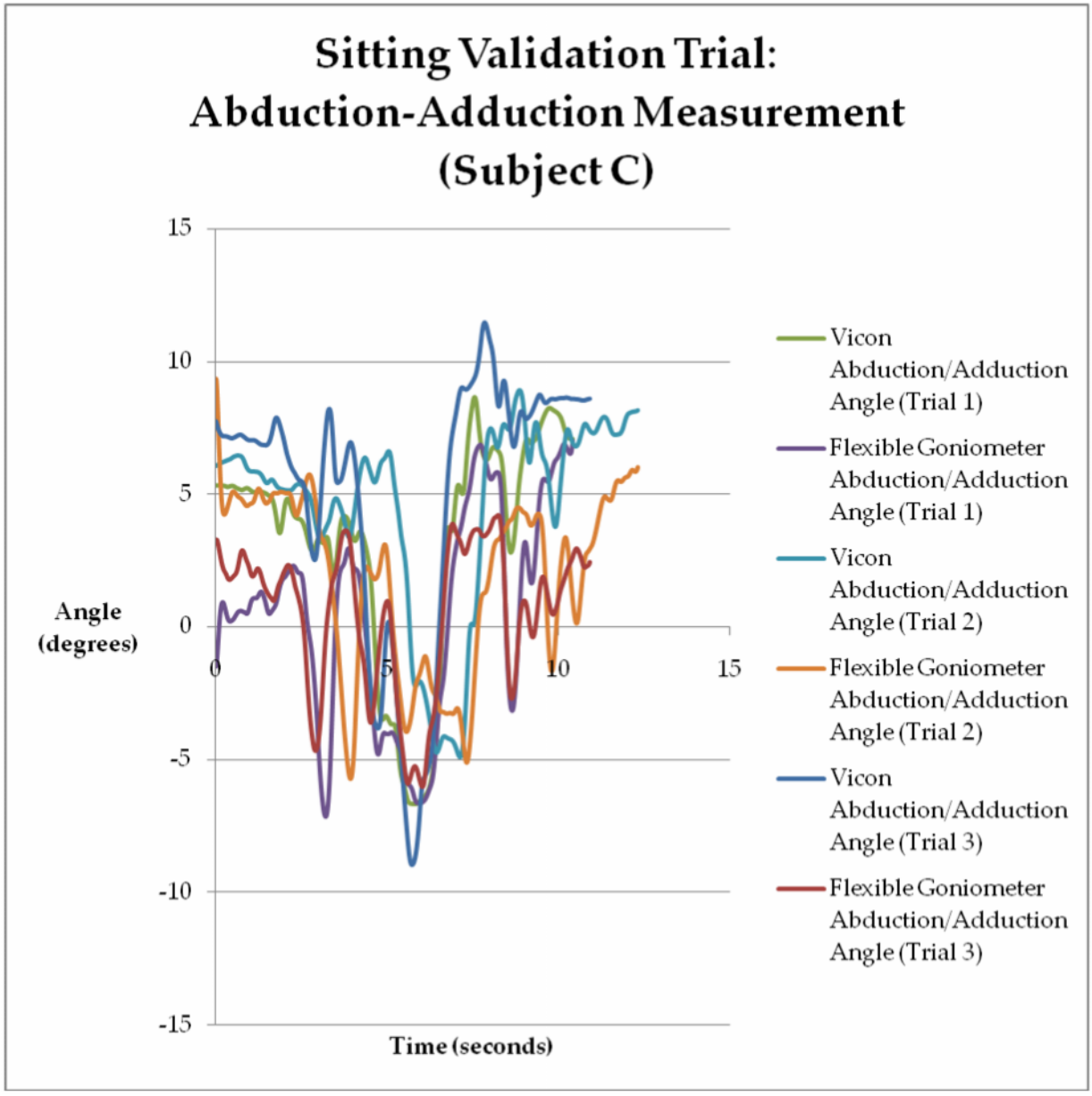

Sitting Validation Trial:
Flexion-Extension
(Subject A)
Angle (degrees)
120
100
80
60
40
20
0
-20
-40
0
2
4
6
8
10
Time (seconds)
Vicon Flexion/Extension Angle (Trial 1)
Flexible Goniometer Flexion/Extension Angle (Trial 1)
Vicon Flexion/Extension Angle (Trial 2)
Flexible Goniometer Flexion/Extension Angle (Trial 2)
Vicon Flexion/Extension Angle (Trial 3)
Flexible Goniometer Flexion/Extension Angle (Trial 3)


Sitting Validation Trial:
Abduction/Adduction Measurements
(Subject A)
Angle (degrees)
25
20
15
10
5
0
-5
-10
-15
-20
0
2
4
6
8
10
Time (seconds)
Vicon Flexion/Extension Angle (Trial 1)
Flexible Goniometer Abduction/Adduction Angle (Trial 1)
Vicon Abduction/Adduction Angle (Trial 2)
Flexible Goniometer Abduction/Adduction Angle (Trial 2)
Vicon Abduction/Adduction Angle (Trial 3)
Flexible Goniometer Abduction/Adduction Angle (Trial 3)


Sitting Validation Trial:
Flexion-Extension Measurement
(Subject B)
Angle (degrees)
120
100
80
60
40
20
0
-20
-40
0
2
4
6
8
10
Time (seconds)
Vicon Flexion/Extension Angle (Trial 1)
Flexible Goniometer Flexion/Extension Angle (Trial 1)
Vicon Flexion/Extension Angle (Trial 2)
Flexible Goniometer Flexion/Extension Angle (Trial 2)
Vicon Flexion/Extension Angle (Trial 3)
Flexible Goniometer Flexion/Extension Angle (Trial 3)


Sitting Validation Trial:
Abduction-Adduction Measurements
(Subject B)
Angle (degrees)
30
25
20
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
Time (seconds)
Vicon Abduction/Adduction Angle (Trial 1)
Flexible Goniometer Abduction/Adduction Angle (Trial 1)
Vicon Abduction/Adduction Angle (Trial 2)
Flexible Goniometer Abduction/Adduction (Trial 2)


Sitting Validation Trial:
Flexion-Extension Measurements
(Subject C)
120
100
80
60
40
20
0
-20
-40
0
5
10
15
Angle (degrees)
Time (seconds)
Vicon Flexion/Extension Angle (Trial 1)
Flexible Goniometer Flexion/Extension Angle (Trial 1)
Vicon Flexion/Extension Angle (Trial 2)
Flexible Goniometer Flexion/Extension Angle (Trial 2)
Vicon Flexion/Extension Angle (Trial 3)
Flexible Goniometer Flexion/Extension Angle (Trial 3)


Sitting Validation Trial:
Abduction-Adduction Measurement
(Subject C)
Angle (degrees)
15
10
5
0
-5
-10
-15
0
5
10
15
Time (seconds)
Vicon Abduction/Adduction Angle (Trial 1)
Flexible Goniometer Abduction/Adduction Angle (Trial 1)
Vicon Abduction/Adduction Angle (Trial 2)
Flexible Goniometer Abduction/Adduction Angle (Trial 2)
Vicon Abduction/Adduction Angle (Trial 3)
Flexible Goniometer Abduction/Adduction Angle (Trial 3)