ARE MEASUREMENTS OF HIP EXTENSION AND ANTERIOR PELVIC TILT TAKEN FROM STATIC PHOTOGRAPGHS DURING A CONSTRAINED FORWARD LUNGE TEST VALID AND RELIABLE IN HEALTHY ADULT RUNNERS?

by

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Submitted in partial fulfilment of the requirements
for the degree of Master of Science

at

Dalhousie University
Halifax, Nova Scotia
August 2011

DALHOUSIE UNIVERSITY

SCHOOL OF HEALTH AND HUMAN PERFORMANCE

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled "ARE MEASUREMENTS OF HIP EXTENSION AND ANTERIOR PELVIC TILT TAKEN FROM STATIC PHOTOGRAPHS DURING A CONSTRAINED FORWARD LUNGE TEST VALID AND RELIABLE IN HEALTHY ADULT RUNNERS?" by Jason Gray in partial fulfilment of the requirements for the degree of Master of Science.

Dated: August 10, 2011

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DALHOUSIE UNIVERSITY

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DEPARTMENT OR SCHOOL: School of Health and Human Performance

DEGREE: MSc CONVOCATION: October YEAR: 2011

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DEDICATION PAGE

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ABSTRACT

The aim of this study was to determine the concurrent validity, test-retest intra-rater reliability, and test-retest inter-rater reliability of photographic measures of anterior pelvic tilt range of motion (APT ROM) and hip extension ROM range of motion (HE ROM) during a constrained forward lunge test (CFLT) in healthy adult runners. Measurements of start, end, and range of motion (ROM) variables for APT and HE motion were taken from an Optorak kinematic measurement system and from printed photographs extracted from digital video footage using a protractor. A total of 13 healthy adult male and female recreational runners participated in the study. Measures of APT ROM and HE ROM were found to be valid compared to Optorak measures, with intraclass correlation coefficients (ICC) of 0.94 and 0.99 respectively, and limits of agreement of -1.42 ± 1.99 degrees and 0.41 ± 2.13 degrees respectively. APT ROM and HE ROM demonstrated high between-day intra-rater reliability with ICCs ranging from 0.75 to 0.91 and within-day inter-rater reliability with ICCs ranging from 0.86-0.90. For between day intra-rater measurements smallest detectable differences (SDDs) ranged from 5.59 to 4.12 for APT ROM and from 9.08 to 11.08 for HE ROM. The present study suggests that photographic measurements of APT ROM and HE ROM during a CFLT are valid and reliable in healthy adult runners; however, these measurements display a low sensitivity with respect to detecting changes between trials.

LIST OF ABBREVIATIONS USED

APT	Anterior Pelvic Tilt
HE	Hip Extension
ASIS	Anterior Superior Iliac Spine
PSIS	Posterior Superior Iliac Spine
CFLT	Constrained Forward Lunge Test
ROM	Range of Motion
2D	Two Dimensional
3D	Three Dimensional
ICC	Intraclass Correlation Coefficient
SEM	Standard Error of Measurement
SDD	Smallest Detectable Difference
LCS	Lower Crossed Syndrome
LPH	Lumbar-Pelvic-Hip
FPT	Functional Performance Test
ANOVA	Analysis of Variance
LOA	Limits of Agreement
BMS	Between Subject Mean Square
EMS	Error Mean Square
RMS	Between Raters Mean Square

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. Michel Ladouceur for his continued support, guidance, and patience in working with me during this project. I must also thanks my committee members, Dr. Lori Livingston, for her early guidance and ongoing support, and Dr. Anne Fenety, for her insight and expertise of clinical testing and statistical analysis. I would also like to thank Dr. Carol Putnam for her tremendous help and guidance with this project as well.

CHAPTER 1: INTRODUCTION

During the push-off phase of running, the thigh rotates posteriorly behind the body in the sagittal plane. Although this is a tri-planar motion involving the lumbar spine, pelvis, and thigh, this posterior rotation of the thigh is primarily accomplished through a combination of hip extension and anterior pelvic tilt (APT). An inverse relationship between peak hip extension and peak APT during running has been demonstrated such that runners who display a smaller magnitude of peak hip extension also display a greater magnitude of peak APT (Franz, Paylo, Dicharry, Riley, & Kerrigan, 2009; Schache, Blanch, & Murphy, 2000). Increased APT during running has been suggested as a predisposing factor to a number of potential running injuries. For example, a strong correlation has been reported between peak APT and peak lumbar lordosis during running (Schache, Blanch, Rath, Wrigley, & Bennell, 2002), which is thought to be related to the onset of back pain in runners due to the repetitive impingement of the lumbar facets (Jackson & Sutker, 1982). It is therefore important, from a clinical perspective, to be able to accurately and reliably measure hip extension and APT utilized to rotate the thigh posteriorly behind the body.

In the running biomechanics literature, hip extension is commonly defined as a backward rotation of the thigh relative to the pelvis. The neutral (zero degrees of extension) position of the hip is designated as the point at which the longitudinal axis of the thigh (greater trochanter to lateral femoral condyle) is perpendicular to a line connecting the anterior and posterior superior iliac spines (Figure 1) (Franz et al.,2009; Schache et al., 2000; Schache, Blanch, Rath, Wrigley, & Bennell, 2003). The neutral (zero degrees) position of pelvic tilt is most commonly defined as the position in which a line connecting the anterior and posterior iliac spines is horizontal within a global coordinate system (Franz et al., 2009; Ounpuu, 1990; Schache et al., 2000, 2001, 2003; Whittle et al., 2000). Anterior pelvic tilt (APT) is defined as a forward rotation of the pelvis in the sagittal plane such that the anterior superior iliac spine (ASIS) is lower than the posterior superior iliac spine (PSIS) (Figure 1).

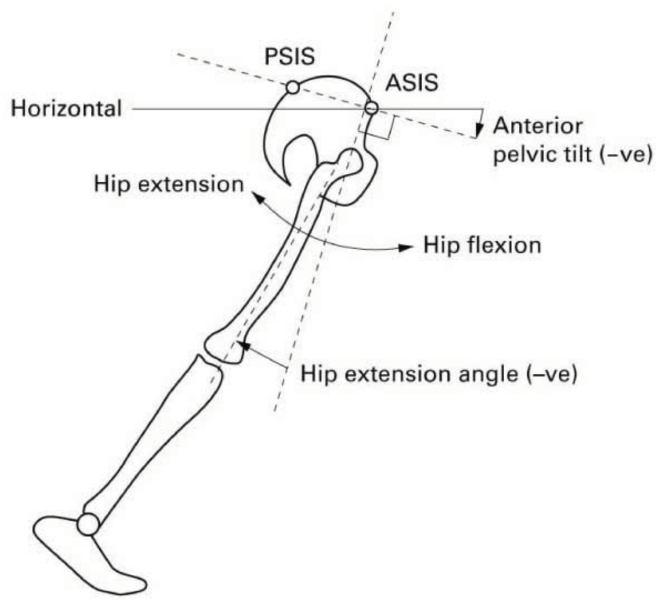

Figure 1. Diagrammatic representation of the measurement of hip extension and APT. The neutral position of the hip is designated as the point at which the longitudinal axis of the thigh is perpendicular to a line connecting the anterior and posterior superior iliac spines. The neutral position of pelvic tilt is defined as the position in which a line connecting the ASIS and PSIS is horizontal within a global coordinate system, with anterior pelvic tilt (APT) defined as a forward rotation of the pelvis in the sagittal plane such that the ASIS is lower than the PSIS. Adapted from Schache et al., 2000.

Restricted hip extension flexibility due to limitations in the hip flexor muscles and hip joint capsule has been proposed as a possible cause of increased APT in running (Franz et al., 2009; Godges, Macrae, & Engelke, 1993; Schache et al., 2000). In an attempt to verify this, researchers have correlated static hip flexibility and dynamic motion of the hip and pelvis. Schache et al. (2000) found no correlation between static, passive hip extension as measured by the Modified Thomas Test, a common clinical test used to measure hip extension flexibility, and the degrees of peak hip extension or APT during running. Similar results were found by Lee, Kerrigan, and Croce (1997) for walking.

Franz et al. (2009) argued that the lack of correlation between passive and dynamic measures of hip extension may simply reflect a limitation of the Modified Thomas Test itself. Schache et al. (2000) and Godges et al. (1993) suggested that differences with regard to the position of the pelvis in the Modified Thomas Test and running may account for the lack of correlation between the static and dynamic measures. As well, Schache et al. (2000) argued that static flexibility may not be the only factor governing the degree of peak hip extension or APT when running at sub maximal speeds, suggesting complex dynamic neuro-motor patterns may also play a role.

The lack of correlation between measures of hip extension taken during the Modified Thomas Test and measures of hip extension and APT seen during running underscores the need for a better clinical test to measure the degrees of hip extension and APT used to rotate the thigh posteriorly behind the body. One possible solution may be to measure hip extension and APT during a forward lunge movement, which is a weight bearing, multi-joint movement performed by having the patient step forward with one leg, leaving the trailing leg outstretched behind them (Figure 2). The use of weight bearing multi-joint movements, commonly referred to as functional performance tests, has been advocated to better assess joint and segmental motion utilized during dynamic activities (Bennell, Talbot, Techovanich, & Kelly, 1998; Cook, 2003; Gray, 2001; Liebenson, 2007). For example, both the Squat and Lunge movements have been suggested as tests for subtalar joint hyper pronation (Cook, 2003; Liebenson, 2007) and ankle dorsiflexion (Bennell et al., 1998; Cook, 2003; Liebenson, 2007). As a clinical test to measure hip extension and APT a Forward Lunge is appealing as it is simple, quick, easy to administer, and the degrees of hip extension and APT can be quantified using inexpensive clinical tools.

Although a Forward Lunge is commonly used as a test by many clinicians, and various forms of the test are included in several textbooks (Cook, 2003; Liebenson, 2007; Reiman & Manske, 2009), there is little consistency in how the Forward Lunge is administered, and there is a lack of information regarding the validity and test-retest reliability of hip extension and APT measures taken during a Forward Lunge.

Figure 2. A forward lunge is a weight bearing, multi-joint movement performed by having the patient step forward with one leg, leaving the trailing leg outstretched behind them. To better standardize the forward lunge movement for this study a Constrained Forward Lunge Test (CFLT) was used in which the step length and position of the lead leg was controlled. To represent the pelvis markers were attached to the anterior superior iliac spine (ASIS) and posterior iliac spine (PSIS). Markers attached to the greater trochanter and lateral femoral condyle were used to represent the thigh.

If a Forward Lunge is to be used as a clinical test to assess the degrees of hip extension and APT utilized to rotate the thigh posteriorly behind the body, a standardized procedure for administering the test must be established. One possible solution may be to use a Constrained Forward Lunge Test (CFLT), in which the step length and lead leg position is controlled (Figure 2). While constraining the forward lunge movement may yield different information compared to an unconstrained, free lunge movement (such as different end range positions of the thigh and pelvis), this constraint would presumably provide more consistency in how the test was administered between multiple testing sessions and between examiners, and would provide a greater likelihood of obtaining reliable measurements.

In addition to a standardized testing procedure, if the CFLT is to be used clinically, information regarding the validity and reliability of the test must be gathered. Validity of a clinical test is typically determined by its concurrent validity, which involves comparing one measurement with another accepted test or measurement that is administered at or about the same time (Thomas, Nelson, & Silverman, 2005). A reliable test is one that has small within-individual variation, and a high test-retest correlation between repeated tests (Soper, Reid, & Hume, 2004). Both the reliability and validity of range of motion (ROM) measurements depends largely on the standardization of test procedures (Gajdosk & Bohannon, 1987). A final consideration of a clinical test is that it should reliably approximate the ranges of motion seen during functional activities. For example, if a CFLT is to be a relevant clinical test to measure hip extension and APT in runners, the ranges of hip extension and APT demonstrated during the test should approximate those typically seen during running.

1.1 Purposes of the Study

The purposes of this study are to 1) determine the validity, intra-rater reliability, and inter-rater reliability of photographic measurements of hip extension and APT taken during a Constrained Forward Lunge Test (CFLT); 2) to determine the relationship between hip extension and APT during the Constrained Forward Lunge; 3) to establish descriptive data for normal peak APT, normal APT ROM, normal peak hip extension, and normal hip extension ROM in healthy male and female adult runners during the CFLT; and, 4) to compare on a descriptive level the degrees of peak hip extension and APT demonstrated by runners during the CFLT with the ranges of these measures as presented in the running biomechanics literature.

1.2 Research Question

Are measurements of hip extension and anterior pelvic tilt taken from static two-dimensional (2D) photographs during a Constrained Forward Lunge Test (CFLT) valid and reliable in healthy adult runners?

1.3 Subsidiary Questions

To determine validity:

1. Are there significant differences between static 2D photographic measures of APT and hip extension taken during a CFLT and those taken with an optoelectric kinematic measurement system as determined by Bland-Altman analysis?
2. What is the strength of the relationship between static 2D photographic measures of APT and hip extension taken during a CFLT and those taken with an optoelectric kinematic measurement system as determined by intraclass correlation coefficients (ICC(2,k))?
3. Do measurements of hip extension and APT taken during a CFLT fall within the ranges of those measures presented in the running biomechanics literature?

To determine reliability:

4. What is the inter-rater and intra-rater reliability of static 2D photographic measurements of hip extension and APT taken from duplicate copies of the same picture on different occasions?
5. What is the inter-rater and intra-rater reliability of static 2D photographic measurements of hip extension and APT taken from different trials of the Constrained Forward Lunge performed on the same day?
6. What is the standard error of measurement (SEM) of static 2D photographic measurements of hip extension and APT taken by single and multiple raters from different trials of the Constrained Forward Lunge performed on the same day?
7. What is the intra-rater reliability of static 2D photographic measurements of hip extension and APT taken from different trials of the CFLT performed on different days?
8. What is the SEM of static 2D photographic measurements of hip extension and APT taken by a single rater from trials of the Constrained Forward Lunge performed on different days?

Additional Questions:

9. Is there a relationship between the degree of peak hip extension and peak APT utilized during the CFLT?
10. What are normal values for peak APT, APT ROM, peak hip extension, and hip extension ROM in healthy adult runners during the CFLT?

1.4 Assumptions

1. There will be minimal movement of markers attached to the skin / compression shorts.
2. The sample population in this study is similar to that seen in other studies in the running biomechanics literature.

1.5 Definition of Terms

Anterior Pelvic Tilt (APT) – A forward rotation of the pelvis in the sagittal plane such that the anterior superior iliac spine (ASIS) is lower than the posterior superior iliac spine (PSIS) (Franz et al., 2009; Schache et al., 2000, 2001, 2002, 2003; Whittle, Levine, & Pharo, 2000; Ounpuu, 1990).

Hip Extension – A backward rotation of the thigh relative to the pelvis. The neutral (zero degrees of extension) position of the hip is designated as the point at which the longitudinal axis (greater trochanter to lateral femoral condyle) is perpendicular to a line connecting the anterior and posterior superior iliac spines (Franz et al.,2009; Schache et al.,2000, 2003).

Thomas Test - The standard Thomas Test, as described by Dutton (2008) involves the patient lying supine on an exam table while flexing one leg up towards their chest until their lumbar spine begins to flex. The clinician then assesses whether or not the thigh of the extended leg maintains full contact with the surface of the exam table. If the leg is raised off the table the test is considered positive, indicating a decrease in flexibility in the rectus femoris or iliopsoas muscle, or both.

Modified Thomas Test – The Modified Thomas Test, as described by Dutton (2008), requires the patient to sit on the end of an exam table. From this position the patient is asked to lie down while bringing both knees to their chest. While the left hip is held in maximum flexion with the arms, the right limb is lowered over the edge of the table towards the floor. In this position the thigh should be horizontal and neither abducted nor adducted, with the lower leg perpendicular to the thigh and in neutral rotation. If the thigh is unable to reach a horizontal position a decrease in flexibility in the iliopsoas and/or the rectus femoris muscle should be suspected. If pushing the knee into further flexion causes an increase in hip flexion (seen as the thigh raising further off the table) the rectus femoris is implicated. If pushing the knee into further flexion does not increase hip flexion the iliopsoas is implicated.

Lunge Test – The Lunge Test, as described by Liebenson (2007), can be used to assess lower extremity strength, flexibility, and balance. It is performed by having the participant step forward and kneel down towards the floor with the opposite knee, then rise back up to a standing position.

Constrained Forward Lunge Test (CFLT) – A Lunge Test in which the step length and position of the lead leg is constrained for the purposes of test standardization. The CFLT is performed by placing a large box in front of the participants' toes at a distance that is equal to their leg length, as measured from the greater trochanter to the floor. From a relaxed standing position, the participant then steps forward to bring their toes and knee and of their lead leg into contact with the box while their trail leg is relaxed with their knee bent towards the floor.

Validity – The extent to which an instrument accurately measures what it is supposed to measure (Berg & Latin, 2008).

Concurrent Validity - A type of validity that involves correlating a measurement or test with some criterion that is administered at or about the same time (i.e. concurrently) (Thomas, Nelson, & Silverman., 2005).

Reliability – The extent to which test scores are repeatable (Berg & Latin, 2008).

Intra-rater reliability - The level of agreement among measurements taken by the same rater.

Inter-rater reliability - The level of agreement among measurements taken by multiple raters.

Within-trial reliability – The reliability of repeated measurements taken from the same trial.

Within-day reliability - The reliability of repeated measurements taken from multiple trials performed on the same occasion.

Between-day reliability - The reliability of repeated measurements taken from trials performed on different days.

Intraclass Correlation Coefficient (ICC) - The correlation between one measurement on a target and another measurement obtained on that target (Shrout & Fleiss, 1979).

Standard Error of Measurement (SEM) – The amount of measurement error, derived by taking the square root of the error variance (Roebroek, Harlaar, & Lankhorst, 1993).

Smallest detectable difference (SDD) – The smallest amount of change from one test to another that can be considered real (Roebroek et al., 1993).

CHAPTER 2: LITERATURE REVIEW

2.1 Basic Anatomy and Range of Motion of the Hip and Pelvis

Throughout this review, references are made to the hip-pelvis complex and to anatomical structures that influence the sagittal plane motion of this region. Therefore, a brief description of the relevant anatomy of the hip-pelvis complex is presented.

2.1.1 The Hip

The hip joint is a multiaxial ball-and-socket joint formed between the head of the femur and the acetabulum of the pelvis. This anatomical configuration allows motion in the sagittal (flexion-extension), frontal (abduction-adduction), and transverse (internal rotation – external rotation) planes. The deep insertion of the head of the femur into the acetabulum provides maximum stability to the hip (Magee, 1997). Surrounding the hip joint is a strong joint capsule along with the iliofemoral, ischiofemoral, and pubofemoral ligaments. The joint capsule and each of the three hip ligaments are passive constraints which will prevent excessive hip extension. The pubofemoral ligament will also prevent excessive abduction. All three femoral ligaments will also limit medial rotation of the femur. The close packed position of the hip, defined by Magee (1997) as the position in which the two joint surfaces are fully compressed and the ligaments and capsule of the joint are maximally tight, is a combination of extension, medial rotation, and abduction. As a result, the degree of available hip extension will be less when the hip is also in an abducted and medially rotated position. In addition to the joint capsule and surrounding ligaments, muscles will also influence ROM of the hip in the sagittal plane. With respect to the sagittal plane, Neumann (2010) has classified muscles as primary and secondary with respect to their capacity to flex or extend the hip (Table 1). Muscles classified as hip flexors can also restrict hip extension, and vice versa.

Table 1. Primary and secondary hip flexors and extensors (Adapted from Neuman 2010)

Muscles	Primary	Secondary
Flexors	• Iliopsoas • Sartorius • Tensor fasciae latae • Rectus femoris • Adductor longus • Pectineus	• Adductor brevis • Gracilis • Gluteus minimus (anterior fibers)
Extensors	• Gluteus maximus • Adductor magnus (posterior head) • Biceps femoris (long head) • Semitendinosus • Semimembranosus	• Gluteus medius (middle and posterior fibers) • Adductor magnus (anterior head)

2.1.2 The Pelvis

The pelvis is comprised of the right and left pelvic bones (inominate bones) and the sacrum. Each pelvic bone connects to the sacrum via the sacroiliac joint, and to each other via the pubic symphysis. The pelvis sits atop the femora, with the hip joints acting as a pivot point for the pelvis and trunk (Neumann, 2010). Movement and orientation of the pelvis in the sagittal plane is commonly referred to as pelvic tilt. Pelvic tilt is largely influenced by the muscles of the lumbo-pelvic-hip region. A muscle imbalance is an abnormality in the ratio of strength and/or flexibility of the agonist and antagonist muscles acting across a joint (Kendall et al., 1993). An imbalance in the muscles surrounding the pelvis has the potential to affect the sagittal plane orientation of the pelvis in both standing posture as well as during dynamic movement. A common muscle imbalance causing increased APT is the lower crossed syndrome (LCS). Originally proposed by Janda, the LCS is characterized by a combination of tightness in the short hip flexors and erector spinae muscles and weakness/lengthening of the abdominal and gluteal muscles (Janda & Schmidt, 1980). LCS is the most commonly referenced muscle imbalance causing increased APT, however, Neumann (2010) states any muscle capable of flexing the hip relative to the pelvis is also capable of anteriorly tilting the pelvis on the femurs. For this reason, tightness of any of the primary or secondary hip flexors (Table 1) would, in theory, contribute to greater APT and exaggerated lumbar lordosis (Neumann, 2010).

2.1.3 Normal Passive Hip Extension

Passive ROM is defined as the movement through available, pain-free range of motion, performed by another individual without active participation by the subject (Kendall et al., 1993). Passive ROM is affected by inert (i.e. bone, ligament, joint capsule) and contractile (i.e. tension produced by antagonistic muscles/tendons) tissues, and is thought to be a measure of the maximum achievable ROM of a given joint (Holt & Smith, 1983, as cited in Robertson, 2001).

Hip extension occurs when the hip joint rotates about a coronal axis, in the sagittal plane in the posterior direction (Kendal et al. 1993). As seen in Table 2, the average value for normal hip extension ranges from +12.3 to -31.2 degrees, with most studies reporting a mean of approximately -10 to -20 degrees of hip extension. Much of the variability seen across studies is likely due to differences in subject positioning and study methodology.

The two most common positions used for measuring hip extension in research, as well as in clinical practice, are prone hip extension, which involves the subject lying prone while an examiner passively extends the thigh, and the Modified Thomas Test, which involves the subject lying supine with the leg to be tested hanging freely off an examination table and the contralateral leg flexed to their chest (Robertson, 2001). Although hip joint extension occurs as a result of movement of the thigh relative to the pelvis neither prone hip extension or the Modifed Thomas Test use the pelvis as a reference point during standard testing procedures. Instead, these tests generally measure the position of the thigh relative to the horizontal or relative to the midline of the trunk. This is a problem as without directly measuring the position of the thigh relative to the pelvis, the resulting thigh angle measurement will represent a combination of both thigh and pelvic motion, and will not provide an accurate measure of hip joint extension. Furthermore, since the trunk is flexible and is able to rotate and bend backwards or forwards, it is difficult ensure the position of the trunk is consistent across subjects or remains consistent from one test to another.

Table 2. Maximum passive hip extension for normal subjects from the literature.

Authors	Sample	Instrument	Measurement Position	Measurement Angle	Mean Hip Extension (positive values indicate flexion)
Bach et al. (1985)	91 subjects	Goniometer	Modified Thomas Test	Measured angle of the thigh with respect to the horizontal	**Runners** R: -19.33 (SD 7.43) L: -19.71 (SD 7.98) **Non-runners** R: -22.91 (SD 7.12) L: -20.19 (6.67)
Harvey (1998)	117 Elite Athletes	Goniometer	Modified Thomas Test	Not reported	Rowing: -10.73 (SD 5.97) Basketball: -11.82 (SD 4.89) Running: -14.15 (SD 4.67) Tennis: -10.93 (SD 6.01) Grand mean: - 11.91 (5.57)
Wang et al. (1993)	40 subjects (20 runners / 20 non-runners)	Goniometer	Modified Thomas Test (with knee extended)	Measured angle formed between the midline of the trunk and long axis of the femur	**Runners** Male: -8 (SD 6) Female: -11 (SD 6) **Non-runners** Male: -8 (6) Female: -8 (5)

Authors	**Sample**	**Instrument**	**Measurement Position**	**Measurement Angle**	**Mean Hip Extension** (positive values indicate flexion)
Wang et al. (1993)	40 subjects (20 runners / 20 non-runners)	Goniometer	Modified Thomas Test (with knee flexed)	Measured angle formed between the midline of the trunk and long axis of the femur	**Runners** Male: +2 (SD 7) Female: -4 (SD 8) **Non-runners** Male: -3 (4) Female: -3 (4)
Schache et al. (2000)	14 elite runners (10 male; 4 female)	Goniometer	Modified Thomas Test	Measured angle formed between the thigh and the horizontal	-17.4
Young et al. (2003)	16 competitive male Australian rules footballers	2D motion analysis system	Modified Thomas Test	Measured angle formed between the thigh and the horizontal	-13.7 (SD 7.8)
Mundale et al. (1956)	35 subjects	Goniometer	Standing with trunk hyperextension Prone (with pelvic stabilization)	Measured angle formed between axis of femur and ASIS-PSIS plane.	*Males: +5.1 *Females: +7.6 *Males: +10.1 *Females: +12.3

Table 2 continued

Authors	Sample	Instrument	Measurement Position	Measurement Angle	Mean Hip Extension (positive values indicate flexion)
Roaas & Andersson (1982)	210 males aged 30-40 yrs.	Goniometer	Prone (knee flexed)	Not reported	R: - 9.4 (SD 5.3) L: - 9.5 (SD 5.2)
Ellis & Stowe (1982)	160 subjects	Goniometer	Prone with manual pelvic stabilization	Measured angle between the neutral axis of the thigh and waist	**Males** 10-20 yrs: -30.1 (SD 8.1) 20-30 yrs: -31.2 (SD 5.9) 30-40 yrs: -26.8 (SD 9.6) 40-50 yrs: -17.3 (SD 1.5) 50-60 yrs: -13.8 (SD 8.1) 60-70 yrs: -9.6 (SD 8.4) 70-80 yrs: -11.1 (SD 10.5) 80+ yrs: -2.3 (SD 4.0) **Females** 10-20 yrs: -31.1 (SD 2.8) 20-30 yrs: -25.0 (SD 5.8) 30-40 yrs: -23.7 (SD 1.5) 40-50 yrs: -21.7 (SD 5.6) 50-60 yrs: -13.3 (SD 7.6) 60-70 yrs: -16.0 (SD 8.9) 70-80 yrs: -10.6 (SD 9.2) 80+ yrs: -5.0 (SD 5.1)

Table 2 Continued.

Variability in hip extension measures using the Modified Thomas Test may also include differences in methodology between studies. For example, some studies included a warm-up which included stretching of the hip flexors prior to data collection (Bach, Green, Jensen, & Savinar, 1985; Young, Clothier, Otago, Bruce, & Liddell, 2003) while other studies did not (Harvey, 1998; Schache et al., 2000; Wang, Whitney, Burdett, & Jansky, 1993). Furthermore, Wang et al. (1993) measured the angle of the thigh relative to the midline of the trunk, while other studies (Bach et al., 1985; Schache et al., 2000; Young et al., 2003) measured the angle of the thigh relative to the horizontal. This may explain the low hip extension angles reported by Wang et al. (1993), however, this assumption needs to be applied with caution as it is based on the comparison of only four studies, and other factors such as knee position may also play a role. Differences in the position of the knee may contribute to the variability in hip extension measures during the Modified Thomas Test. Wang et al. (1993) held the knee of the leg being tested in a position of 90 degrees, while other studies (Bach et al., 1985; Harvey, 1998; Schache et al., 2000; Young et al., 2003) did not standardize the position of the knee and allowed it to hang freely off the examination table. Flexing the knee to 90 degrees will place more tension on the rectus femoris, which may in turn limit the degree of hip extension.

Differences in the angles measured, and position of the knee can also been seen in studies measuring prone hip extension. Mundale, Hislop, Rabideau, and Kottke (1956) measured the angle formed between the long axis of the thigh and a straight line connecting the ASIS and PSIS. Rooas and Andersson (1982) did not specify what angle they measured, and Ellis and Stowe (1982) measured the angle between the thigh and waist, although they did not elaborate on what this meant. With respect to the position of the knee, Rooas and Andersson (1982) held the knee in a flexed position, while Mundale et al. (1956) and Ellis and Stowe (1982) kept the knee extended. Such differences in measurement procedures are likely to contribute to the wide variability in of hip extension measurements across studies (Table 2).

In the running biomechanics literature, hip extension is commonly defined as a backward rotation of the thigh relative to the pelvis. The neutral (zero degrees of extension) position of the hip is designated as the point at which the longitudinal axis of the femur (greater trochanter to lateral femoral condyle) is perpendicular to a line connecting the anterior and posterior superior iliac spines (Franz et al.,2009; Schache et al., 2000, 2003). To the author's knowledge, Mundale et al. (1956) are the only authors to use this convention when studying normal passive hip extension. They found that in normal standing, the hip was in a position of flexion for both men and women (i.e., the angle of hip flexion was 10.5 degrees for men, 15.3 degrees for women). Mundale et al. (1956) recorded the smallest hip angles when subjects stood with the trunk in hyperextension, however, the hip remained in a flexed position relative to the pelvis (+ 5.1 degree for men; +7.6 degrees for women). Only one participant, an athlete involved in vigorous stretching activities, was able to extend his hip past neutral.

In summary, as can be seen in Table 2, a large variability exists in the reported measures of normal hip extension. Much of this variability is most likely due to measuring the angle of the thigh relative to the trunk or horizontal as opposed to the pelvis. It would be advantageous to clinicians if a standardized, accurate, and reproducible method of measuring hip extension relative to the pelvis could be established, and normative data could be collected using this method.

2.1.4 Normal Pelvic Tilt

To the author's knowledge, there is minimal data in the literature reporting normal ranges of pelvic tilt, and this characteristic is not routinely measured in a clinical setting. However, the degree of pelvic tilt during standing is routinely included in a standard orthopaedic examination. Neutral pelvic tilt has traditionally been defined as the position in which the ASIS and the pubic symphysis are in the same vertical plane, with anterior pelvic tilt occurring when the vertical plane through the ASIS is anterior to the pubic symphysis (Kendall et al., 1993). However, as this anatomic relationship is difficult to visualize in a clinical setting, the angular deviation between the horizontal plane and a line connecting the anterior and posterior superior iliac spines is a frequently used clinical assessment of pelvic tilt (Sahrmann, 2002). This is consistent with the definition of pelvic tilt used in the running literature (Franz et al., 2009; Schache et al., 2000, 2002, 2003).

Table 3. Values for pelvic tilt in standing and APT ROM from the literature.

Authors	Sample	Instrument Used	Mean Standing Pelvic Tilt (degrees)	Maximum Active APT ROM (peak active APT during standing – pelvic tilt in normal standing)
Gajdosik et al. (1985)	22 healthy men (mean age 25.2 yrs)	Depth calliper/sliding pointer with trigonomic functions.	Test: 8.35(SD = 4.17) Re-test: 8.53(SD = 4.08)	Test: 12.86 (SD = 5.47) Re-Test: 12.57 (SD = 5.79)
Gilliam et al. (1994)	23 men and women (mean age 23.9)	Inclinometer	**Tester 1:** Test: 8.5 (range: -4.0 - 17.5) Re-test: 7.9 (range: -2.0 - 15.5) **Tester 2:** Test: 5.9 (range: -7.0 – 13.5) Re-test: 5.5 (range: -8.0 – 14.0) **Tester 3** Test: 5.5 (range: -8.5 - 12.5) Re-test: 5.5 (range: -6.0 – 12.5)	Not reported
Gilliam et al. (1994)	15 men and women (mean age 23.9)	Standard roentgenograms	**Radiologist 1:** Test: 11.6 (range: 0 – 28.5) Re-test: 11.7 (range: -3.0 – 28.0) **Radiologist 2:** Test: 14.5 (range: -2.5 – 31.5) Re-test: 15.5 (range: 1.5 – 31.0) **Physical Therapist** Test: 9.1 (range: -4.0 – 21.0)	Not reported

As seen in Table 3, the average value of pelvic tilt in standing, when measured as the angular deviation between the horizontal plane and a line connecting the anterior and posterior superior iliac spines, ranges from 5.5 to 15.5 degrees, indicating the pelvis assumes a position of slight APT in normal standing. The maximum active APT ROM, measured as the difference between maximum active APT during standing and the degree of pelvic tilt during normal standing, is approximately 12 to 13 degrees (Gajdosik, Simpson, Smith, & DonTingy, 1985).

2.2 Kinematics of the Lumbo-Pelvic Region During Running

2.2.1 Running Gait Cycle

Although the running stride is one continuous motion, it is commonly divided into discrete phases to make analysis and discussion of running easier. The gait cycle is the basic unit of measurement of the running stride. A gait cycle begins as one foot makes initial contact with the ground, and ends when the same foot makes contact with the ground once again (Novachek, 1998). The gait cycle can be further divided into stance and swing phases. Stance phase begins as the foot makes initial contact with the ground and lasts until toe-off, when the foot is no longer in contact with the ground. The period of time in which the foot is off the ground is referred to as the swing phase. This phase begins with toe-off and ends with initial contact, at which point one full gait cycle is completed.

2.2.2 Pelvic Motion During Running

Several studies have measured pelvic motion in the sagittal plane during running using 3-dimensional (3D) measurement systems. In all studies reviewed, motion of the pelvis was measured with respect to a global coordinate system. Rotation of the pelvis in the sagittal plane is referred to as pelvic tilt. APT was consistently defined as a position in which the ASIS was lower than the PSIS and was assigned a positive value (Franz et al., 2009; Ounpuu, 1990; Schache et al., 2003, 2002, 2001,2000; Whittle et al., 2000).

The pelvis displays a biphasic movement pattern in the sagittal plane during running (Figure 3) (Schache et al., 2002). The pelvis remains anteriorly tilted during the

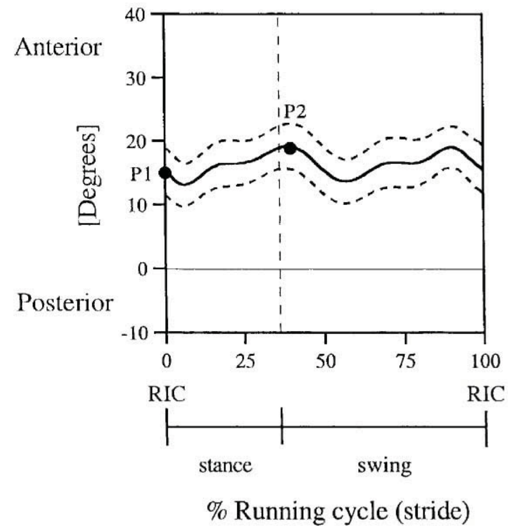

Figure 3. Average curve and standard deviation for pelvic tilt during running. Note the biphasic movement pattern in the sagittal plane with the pelvis reaching its first peak anterior pelvic tilt at or slightly after toe-off. This movement cycle is then repeated following foot strike of the contralateral leg (from Schache et al. 2002).

entire running cycle (Novacheck, 1990; Ounpuu, 1990; Schache et al, 2002). During the late swing phase the pelvis begins to tilt in the posterior direction and reaches its first peak posterior rotation (position of minimum anterior tilt) just after foot strike. The pelvis then rotates anteriorly and reaches its first peak anterior pelvic tilt at or slightly after toe-off. This movement cycle is then repeated following foot strike of the contralateral leg (Schache et al., 2002).

Table 4 provides a summary of the anterior pelvic tilt data recorded during running. There is a wide variability in the average values for peak anterior pelvic tilt between studies, ranging from 16.2 degrees to 22.1 degrees. At least some of this variability may be related to differences in running speed, stride length, study population, and how peak anterior pelvic tilt was defined and measured across studies.

Running speeds ranged from a high of 5.56 m/s (Schache et al., 2000) to a low of 2.23 m/s (Ounpuu, 1990). Schache et al. (2000) used the fastest running speed amongst all studies and also reported the greatest magnitude of peak anterior pelvic tilt (22.1

Table 4. Pelvic kinematics during running from the literature. (Data reported as mean value ± standard deviation (if reported))

Study	**Sample** (all healthy subjects)	**Height** (m) (mean ±SD)	**Running Speed** (m/s)	**Self - selected vs. Forced Speed**	**Peak APT** (degrees) (mean ±SD)	**Amplitude of APT** (max – min) (mean±SD)	**Stride Length** (m) (mean±SD)	**Treadmill vs Overground**
Franz et al. (2009)	38 female 35 male Recreational runners	1.72 ± 0.08	3.17	Self	16.2±6.5	NR	2.30±0.29	treadmill
Schache et al. (2003)	22 male recreational runners	1.77 ±0.05	4.0	Forced	20*	7.8	2.63±0.13	treadmill
Schache et al. (2003)	22 female recreational runners	1.67 ±0.09	4.0	Forced	22*	9.4	2.80±0.17	treadmill
Schache et al. (2002)	20 male recreational runners	1.78±0.46	4.0	Forced	19*	7.6±2.0	NR	treadmill
Schache et al. (2001)	9 male / 1 female recreational runners	1.78 ±0.53	3.98	Self	L: 8.6±3.6 R: 8.6±3.5	NR	L:2.85±0.32 R:2.85±0.32	treadmill

Study	**Sample** (all healthy subjects)	**Height** (m) (mean ±SD)	**Running Speed** (m/s)	**Self - selected vs. Forced Speed**	**Peak APT** (degrees) (mean ±SD)	**Amplitude of APT** (max – min) (mean±SD)	**Stride Length** (m) (mean±SD)	**Treadmill vs Overground**
Schache et al. (2001)	9 male 1 female recreational runners	1.78 ±0.53	3.99	Self	L: 20.6± 2.9 R: 20.4±3.6	NR	L: 2.99±0.30 R: 2.96±0.29	overground
Whittle et al. (2000)	20 females	NR	2.9	Forced	NR	8.9	NR	treadmill
Schache et al. (2000)	10 male 4 female elite runners	Male-1.77 Female-1.68	5.56	Forced	22.1[+]	NR	** 2.06	treadmill
Ounpuu (1990)	3 boys 9 girls Ages 5-11	1.28	2.23	Self	NR	10	1.26	overground

*peak anterior pelvic tilt angles estimated from graphs

**relative stride length expressed as a percentage of height

[+] peak anterior pelvic tilt defined as the position of the pelvis at maximum hip extension and may not reflect a true peak value (see test for explanation).

Table 4 Continued

degrees at 5.56 m/s), while Franz et al. (2009) reported the lowest peak anterior pelvic tilt while studying runners at one of the slowest speeds (16.2 degrees at 3.17 m/s). This suggests that faster running speeds may be associated with a greater magnitude of peak anterior pelvic tilt; although further research is required to better understand this relationship.

Differences in stride length observed across studies may also explain some of the variability in peak anterior pelvic tilt. As can be seen in Table 4, in the studies reviewed stride lengths ranged from 1.26 meters to 2.99 meters, with longer stride lengths being associated with greater peak anterior pelvic tilt angles. Although it seems logical that longer stride lengths would be associated with greater peak APT some studies did not support this notion. Schache et al. (2003) showed that female runners display a greater magnitude of peak anterior pelvic tilt and greater amplitude of pelvic anterior-posterior pelvic tilt compared with male runners, but had shorter stride lengths. Using a forward stepwise regression Schache et al. (2003) found that stride length did not predict the variance in the amplitude of APT. Similarly, relative stride length (stride length as a percentage of height) did not predict peak APT (Schache et al., 2000). On the other hand, Franz et al. (2009) found a statistically significant relationship between stride length and peak anterior pelvic tilt. However, although statistically significant, only a small degree of variance (R^2=0.08) in anterior pelvic tilt during running was found to be explained by changes in stride length.

Differences in the study populations across studies may also contribute to the variability seen in peak APT. Schache et al. (2000) used elite track and field athletes for their study and reported the greatest magnitude of peak anterior pelvic tilt, while other studies, including Franz et al. (2009), used recreational runners. Therefore, it is possible that the greater peak anterior pelvic tilt reported by Schache et al. (2000) may be a factor of running ability or training status as opposed to running speed.

Another issue to consider when comparing the peak anterior pelvic tilt values across studies is how peak anterior pelvic tilt is defined and measured. In some cases peak anterior pelvic tilt was defined as the maximum angle of anterior pelvic tilt to occur over the course of the running gait cycle (Franz et al., 2009; Schache et al., 2001).

However, Schache et at. (2000) defined peak anterior pelvic tilt as the magnitude of anterior pelvic tilt that occurred at the instant of peak hip extension. Franz et al. (2009) found peak anterior pelvic tilt to occur slightly before peak hip extension during running. Therefore, it is possible that the value reported by Schache et al. (2000) may be slightly lower than the true peak value of anterior pelvic tilt.

Marker placements used to measure pelvic motion with respect to a global coordinate system also differed between studies. To define the pelvis Schache et al. (2000;2001;2002;2003) used markers positioned over the right and left anterior superior iliac spines (ASIS) and midway between the posterior superior iliac spines (PSIS) while Franz et al. (2009) assigned virtual markers to the ASIS and PSIS which were associated with a coordinate system defined by a rigid marker cluster adhered to the subjects sacrum. Ounpuu (1990) did not report the location of marker placement, only that retroreflective balls marked specific anatomic locations, and that three markers forming a plane were used on each segment to allow three-dimensional reconstruction.

2.2.3 Lumbar Spine Motion During Running

As seen in Table 5, the amplitude of lumbar spine flexion/extension during running ranges from 10.95 to 21.45 degrees, with the average position ranging from 22.9 to 26.44 degrees of extension. During the running gait cycle, the lumbar spine displays a biphasic movement pattern. During the early stance phase the lumbar spine flexes slightly. By midstance, the lumbar spine begins extending. The lumbar spine reaches its first extension peak immediately before toe off. This lumbar spine movement cycle is then repeated following initial contact of the contralateral extremity (Schache et al. 2002, Saunders, Schache, Rath, & Hodges, 2005).

Schache et al. (2002) have shown that flexion-extension of the lumbar spine and anterior-posterior tilt of the pelvis is highly coordinated during running. Essentially, as anterior tilt of the pelvis increased during terminal stance, extension of the lumbar spine also increased. The lumbar spine reached a position of maximum extension immediately before toe off. The pelvis reached a position of maximum anterior pelvic tilt very soon after toe-off.

Sagittal plane lumbo-pelvic motion has also been shown to vary with speed of locomotion. In a study investigating the effects of different walking and running speeds on lumbo-pelvic kinematics and trunk muscle activity, Saunders et al. (2005) measured 3D kinematic motion of the lumbar spine relative to the pelvis in 6 males and 1 female participant during treadmill running. There was no change in timing of the biphasic flexion and extension peaks in lumbar spine motion across the running speeds from 2 to 5 m/s, although the amplitudes of this motion increased with increasing running speed.

Table 5. Average position and amplitude of the lumbar spine during running from the literature. (Data reported as mean values ± standard deviation (if reported)).

Study	**Population**	**Running Speed** (m/s)	**Amplitude of L/S flexion/extension** (degrees) (maximum flexion – maximum extension) (mean±SD)	**Average Position** (degrees) (positive value indicates lumbar spine extension) (mean±SD)
Schache et al. 2002	20 male runners	4.0	13.3±3.8	22.9±6.2
Levine et al. 2007	20 females	2.9	10.95 to 21.45*	26.44±6.77
Whittle et al. 2000	20 females	2.9	12.1	25.9

*reported only as a range

2.2.4 Hip Motion During Running

In running the hip is flexed at foot strike. Through the middle and later stages of stance the hip moves from a flexed to an extended position, reaching a position of peak extension at toe-off (Mann & Hagy, 1980; Novacheck 1990; Ounpuu, 1990; Pink, Perry, Houglum, & Devine, 1994) or slightly after toe-off (Mann, Morgan, & Dougherty, 1986; Schache et al., 2003). The angle of peak hip extension varies among studies and ranges from 5 to 20.5 degrees of extension (Table 6). This is fairly consistent with the typical range of maximal passive hip extension of 10 to 20 degrees (Table 2). The wide range of hip extension is likely influenced by study variables such as measurement techniques and running speed.

Measurement techniques differed slightly between studies. Schache et al. (2000; 2003) measured hip extension as the posterior rotation of the thigh relative to the pelvis. The thigh was represented by markers placed on the lateral femoral condyle and markers mounted on small wands on the lateral aspect of the distal third of the thigh, while the pelvis was represented by markers placed on each ASIS and a marker on the sacrum placed midway between the two PSIS. However, Schache et al. (2003) reported peak hip extension as the degree of maximum hip extension achieved over the entire running stride while Schache et al. (2000) used the degree of hip extension that occurred at the moment of toe-off to represent peak hip extension. Franz et al. (2009) also reported hip extension as the posterior rotation of the thigh with respect to the pelvis and defined peak hip extension as the maximum angle of hip extension achieved over the entire running stride. The thigh was represented using markers placed on each lateral femoral condyle and lateral mid thigh, with the pelvis being represented by virtual markers assigned to the ASIS and PSIS which were associated with a coordinate system defined by a rigid marker cluster adhered to the subjects sacrum.

Studies measuring peak hip extension during running have also differed with respect to running speed. This is likely to account for some of the variability between studies as peak hip extension angle has been shown to increase when running speed increases from slow to moderate speeds (Pink et al., 1994). Pink et al. (1994) reported an increase in peak hip extension from 6 degrees to 11 degrees of hyperextension when subjects increased their running speed from 2.95 m/s to 3.94 m/s.

The relationship between greater peak hip extension angles and running speed can be seen from the data in Table 6. Ounpuu (1980) used the slowest running speed of 2.23 m/s and reported the smallest peak hip extension angle. As speed increases to 3.17 m/s in the study by Franz et al. (2009) and to 4.0 m/s by Schache et al. (2003) the reported peak hip extension angle also increases. The exception to this pattern is seen in the study by Schache et al. (2000), who used the fastest running speed but did not report the largest peak hip extension angle. One possible explanation for this may be that, as stated above, Schache et al. (2000) assumed peak hip extension to occur at toe-off, so he may have underestimated the true peak values. Another possible explanation may be the difference in study populations. Schache et al. (2000) used a group of elite level distance runners, while other studies used either recreational runners (Franz et al., 2009; Pink et al., 1994; Schache et al., 2003) or children (Ounpuu, 1990). It is possible that through training, elite level runners have adapted their running strides to achieve less peak hip extension. Further study is needed to examine this possibility further.

2.3 Relationship Between APT and Hip Extension

During the late stance / early swing phase of running the thigh rotates posteriorly past vertical approximately 20 to 40 degrees (Schache et al., 1999). Posterior rotation of the right thigh past vertical involves small degrees of lumbar spine rotation to the left, pelvic rotation and lateral tilt to the right, and right hip internal rotation and abduction, however, posterior thigh rotation primarily occurs in the sagittal plane as a result of right hip extension and APT. The position of maximum thigh extension occurs at or just after toe off (Schache et al. 1999).

An inverse relationship between peak hip extension and peak APT during running has been demonstrated, such that runners who display a smaller magnitude of peak hip extension also display a greater magnitude of peak APT (Franz et al., 2009; Schache et

Table 6. Peak hip extension during running from the literature.

Study	Study Population	Running Speed (m/s)	Peak Hip Extension (degrees) (mean±SD)
Franz et al. (2009)	73 subjects (35 male, 38 female)	3.17	-14.6±5.6
Schache et al. (2003)	10 subjects (9 males, 1 female)	4.0	L: -17.8±4.2 R: -16.9± 5.0
Schache et al. (2003)	10 subjects (9 males, 1 female)	4.0	L: -20.5±5.6 R: -18.9±5.5
Schache et al. (2000)	14 subjects (10 male, 4 female)	5.56	-11.7 (range = 27.1 to 7.5)
Pink et al. (1994)	14 subjects (9 women, 5 men)	2.95	- 6±5
Pink et al. (1994)	14 subjects (9 women, 5 men)	3.35	- 11±6
Ounpuu (1990)	12 subjects (9 girls, 3 boys)	2.23	- 5

al., 2000). A similar relationship has also been shown to occur in walking (Franz et al., 2009; Lee et al.,1997). There are several possible explanations as to why this relationship occurs, including limitation in passive hip extension flexibility and muscle imbalances around the lumbo-pelvic-hip region.

2.3.1 Anterior Pelvic Tilt and Passive Hip Extension Flexibility

Some authors have suggested that increased APT in running may result from a limitation in hip extension ROM motion due to structural limitations in the hip flexor muscles or hip joint capsule (Franz et al., 2009; Godges, et al., 1993; Schache et al. 2000). Even if a runner demonstrates the normal passive hip extension of 10 to 20 degrees, at some point during the late stance / early swing phase of the stride the hip flexor muscles will reach their limit of extensibility or the hip joint will reach its closed pack position, requiring the pelvis to tilt further anteriorly for the thigh to rotate the typical 20 to 40 degrees behind the body. In any case, it is logical to assume that runners who have restricted hip extension ROM also will demonstrate greater a magnitude of APT compared to those who demonstrate full passive hip extension ROM. However, studies have failed to find a firm relationship between measures of static hip flexibility and dynamic motion of the hip and pelvis. Schache et al. (2000) found no significant correlation between static hip extension range of motion as measured by the Modified Thomas Test and the amount of peak hip extension or peak anterior pelvic tilt in a group of elite runners. Lee et al. (1997) found hip extension flexibility as measured by the Thomas test to be poorly correlated with the amount of peak anterior pelvic tilt during walking ($r = 0.36$, $P = 0.17$).

Several reasons have been proposed for the lack of correlation between the Thomas Test / Modified Thomas Test and dynamic motion of the hip and pelvis. These include limitations of the Modified Thomas Test / Thomas Test itself, differences in the position of the pelvis between the Modified Thomas Test / Thomas Test and running, and the influence of factors other than flexibility in determining the degree of hip extension and APT demonstrated during running.

Franz et al. (2009) argued that the degree of hip extension and APT during running is related to passive hip extension flexibility, and the lack of correlation between the Modified Thomas Test and hip extension during running simply reflects the inability of the Modified Thomas Test to identify this relationship, although they did not elaborate on why this may be. Godges et al. (1993) and Schache et al. (2000) suggested that because the Modified Thomas Test places subjects in a supine position it may not correlate to joint range of motion during multi-segmental, dynamic activities such as walking and running. Schache et al. (2000) recommended that future researchers should consider other tests which better replicate the position of the pelvis during running. This could include keeping the body pelvis in an upright, self supported position so that motion of the pelvis is not restricted. Finally, static flexibility may not be the only factor governing the degree of hip extension ROM or APT when running at sub maximal speeds (Schache et al., 2000). Factors such as muscle balance and posture are also likely to play a role in determining hip and pelvis kinematics seen during running.

Some support for the relationship between hip extension flexibility and peak anterior pelvic tilt during dynamic activities can be seen in a study by Kerrigan et al. (2003), who looked at the effects of a 10-week hip flexor stretching program on peak hip extension and peak APT during walking. Following the 10-week intervention the treatment group was found to have a statistically significant increase in static hip extension flexibility (increasing from 6.1 +/- 2.5 degrees to 7.7 +/- 3.6 degrees, P=0.032). Although not statistically significant, the treatment group also exhibited reduced peak APT during walking at both slow (decreasing from 13.1 +/- 7.3 degrees to 12.3 +/- 5.6 degrees) and fast speeds (decreasing from 14.8 +/- 7.2 degrees to 13.7 +/- 5.6 degrees, P=0.262). As might be suggested, the magnitude of reduction in peak anterior pelvic tilt closely matched the increase in static hip extension flexibility. These findings provide some tentative support for the argument that increased anterior pelvic tilt could result from a limitation in hip extension mobility in walking. However, study participants came from an elderly population, and it cannot be assumed that the same results would apply to a younger population, nor that the results would apply to running.

2.3.2 Anterior Pelvic Tilt and Muscle Imbalances of the Lumbo-Pelvic-Hip Region.

As previously discussed, the orientation of the pelvis in the sagittal plane in an upright posture is largely influenced by muscle balance in the lumbo-pelvic-hip (LPH) region. Muscle tightness of any muscles with the capacity to flex the hip or extend the spine, or weakness in any muscles with the capacity to extend the hip or flex the spine has the potential to create an increase in APT. Increased APT in standing is commonly attributed to LPH muscle imbalances, however pelvic tilt during dynamic activities may also be affected. Tight muscles have a lower threshold of irritability, leading to the muscle being activated earlier than normal in a movement sequence (Norris, 1995). Overactivity of a tight muscle may also lead to reciprocal inhibition of its antagonist muscle and a reprogramming of the motor sequence, further compromising postural and segmental control (Norris, 1995).

With respect to running, under normal conditions the hip flexors, including the psoas and iliacus begin to contract pliometrically late in the stance phase as the hip extends and the thigh moves behind the body (Andersson et al., 1997; McClay, Lake, & Cavanaugh, 1990; Montgomery, Pink, & Perry 1994). It is conceivable that if these muscles were tight they may begin to contract earlier in the gait cycle and reduce the degree of hip extension leading to a possible compensation of increased APT to maintain posterior thigh rotation. In addition, if the hip flexors contract earlier in the gait cycle it will increase the stiffness of these muscles as the thigh is rotating back behind the body, thereby increasing the torque on the pelvis which will pull it further into anterior tilt unless this torque is opposed by antagonistic muscles.

2.3.3 Anatomical Variation and Measures of Anterior Pelvic Tilt / Hip Extension

Using cadaveric pelves, Preece et al. (2009) have shown that with ASISs and pubic symphysis in the same vertical plane (i.e. the neutral position of the pelvis as defined by Kendall et al. (1993)) the angle formed between a line connecting the ASIS and PSIS and the horizontal varies as much as 23 degrees. This finding will clearly have an impact on hip extension and APT measurements and the relationship between hip extension and APT during running when a line connecting the ASIS and PSIS is used a reference point. For example, assuming the same relative positions of the thigh and pelvis, when a line connecting the ASIS and PSIS is more horizontal compared to being tilted more anteriorly, it would result in measurements reflecting a greater degree of hip extension and lesser degree of APT. When a line connecting the ASIS and PSIS is more anteriorly tilted compared to being more horizontal it would result in measurements reflecting a lesser degree of hip extension and greater degree of APT.

At this time, the degree to which anatomic variation of pelvic landmarks affects the measurements of hip extension and APT and the relationship between these variables during running is unknown. Although it is evident that anatomic variation of the pelvis does exist between individuals, the range of inter-subject variability is unclear. As reported above, Preece et al. (2009) showed that the plane of a line connecting the ASIS and PSIS to vary as much as 23 degrees, however, a similar study by Deusinger et al. (1992) reported a range of only 12 degrees. Furthermore, the findings of Preece et al. (2009) and Duesinger et al. (1992) are based on the neutral position of the pelvis as defined by Kendall et al. (1993), however this an arbitrary position and may not reflect a true neutral pelvic position. In any case, anatomical variation in the ASIS and PSIS may make it difficult to make between subject comparisons, or compare individuals to group means. Comparing group means between different studies will be less affected by anatomical variation of the ASIS and PSIS as the variation in the angle of a line connecting the ASIS and PSIS follows a normal distribution (Preece et al., 2009), and the mean represents an average of this variation.

2.4 Biomechanical Factors Associated with Running Injuries

2.4.1 Incidence/Epidemiology of Running Injuries

Studies estimate there are now over 30 million runners, 10 million of whom run on more than 100 days per year, with approximately 1 million runners entering competitive races per year (Ballas, Tytko, & Cookson, 1997; Van Mechelen, 1992). This high participation rate in distance running has been accompanied by an increase in running related injuries. Epidemiological studies of both competitive and recreational runners have estimated that between 55% and 79% of runners will sustain overuse injuries over the course of a year (Bennell & Crossley, 1996; Jacobs & Berson, 1986; Lun, Meeuwisse, Stergiou, Stefanyshyn, 2004; Van Middlekoop, Kolkman, Van Ochten, Bierma-Zeinstra, Koes, 2008). Among those training for marathons, the yearly incidence rate can be as high as 92% (Satterthwaite, Larmer, Gardiner, & Norton, 1996).

Injuries to the back and pelvic region account for approximately 11-13% of all running injuries (Bennell & Crossley, 1996). Although back and pelvis injuries are less common than injuries to other areas such as the lower leg (28%), thigh (22%), and knee

(16%) (Bennell & Crossley, 1996), several case studies have demonstrated that injuries to the back and pelvis can often be debilitating in nature and require prolonged periods of treatment for resolution (Haun et al., 2007; Bono, 2004; Klossner, 2000; Fields et al., 1990).

2.4.2 Biomechanics and Running Injuries

Running overuse injuries are thought to be the result of mechanical overload experienced by the locomotor system (Schache et al, 1999), and generally occur when a structure is exposed to a large number of repetitive forces producing a combined fatigue effect over a period of time (Hreljac, Marshall, & Hume, 2000). Although studies estimate that 60% of running overuse injuries are related to training errors such as increasing volume or intensity too quickly, it has been suggested that most overuse injuries are also associated with some underlying anatomical or biomechanical problem (Hreljac et al. 2000).

A number of studies have attempted to identify abnormal kinematic patterns as potential contributing factors to running overuse injuries. Excessive anterior pelvic tilt during running has been cited as a predisposing factor to hamstring strains (Geraci, 1996), while excessive pelvic lateral tilt has been associated with both iliotibial band syndrome (Anderson, 1991, as cited in Schache et al., 2002) and sacroiliac joint injuries (Lloyd-Smith, Clement, McKenzie, & Taunton, 1985, as cited in Schache et al., 2002). A strong correlation has also been reported between increased anterior pelvic tilt and increased lumbar lordosis during running (Schache et al., 2002). Excessive lumbar lordosis is thought to be related to the onset of back pain in runners as a result of the repetitive impingement of the lumbar facets (Jackson & Sutker, 1982).

2.5 Clinical Assessment of Flexibility and ROM

2.5.1 Relationship Between Clinical Tests and Functional Activities

In a clinical setting, practitioners commonly use clinical/orthopaedic tests such as the Modified Thomas Test to measure hip extension, and standing posture to assess pelvic tilt. As previously stated, it has been shown that the degree of hip extension measured during the Modified Thomas Test does not correlate with the degree of hip extension or APT seen during running (Schache et al., 2000). In contrast, Young et al. (2003) did report a significant moderate correlation between the degree of hip extension measured during a Modified Thomas Test and the peak hip extension angle demonstrated during kicking in Australian rules football (r = .65, P<0.01). Therefore, the Modified Thomas Test is likely a valuable test in some situations, but may not be the most appropriate test for measuring hip extension when working with runners. This underscores the need for a better clinical test to measure the degrees of hip extension and APT used to rotate the thigh posteriorly behind the body

2.5.2 Functional Performance Tests

It has been suggested that dynamic assessment of flexibility and joint ROM might be more appropriate for athletes than traditional static-flexibility measures (Crill, Kolba, & Chleboun., 2004). One potential way to do this may be through the use of functional performance tests (FPTs). FPTs involve observing a patient perform some form of multi-joint movement that mimics realistic functional movements which the patient would perform on a regular basis (Loudon, Weisner, Goist-Foley, Asjes, & Loudon, 2002). Examples of FPTs include the Squat and Lunge tests, both of which have been suggested as tests to assess subtalar hyperpronation and ankle dorsiflexion (Bennell et al. 1998; Cook, 2003; Liebenson, 2007). In theory, since these tests involve dynamic motions which require a combination of strength, flexibility, muscle balance, and learned motor patterns, these tests may provide a more accurate representation of the ROM seen during real life activities such as running. For FPTs to be useful they must be valid, reliable, and to be most effective, must reliably approximate the ranges of motion use during functional activities (Soper, Reid, & Hume, 2004).

2.5.3 The Forward Lunge Test

A forward lunge movement is a common clinical test, performed by having the patient step forward with one leg, leaving the training leg outstretched behind them . It has been suggested that the lunge movement is an amplification of the joint kinetics and kinematics that are used during gait (Crill et al., 2004). Crill et al. (2004) have shown that the step length naturally selected by participants completing a forward lunge task was consistent across trials within and between days. Although the movement of individual joints and segments were not directly measured, the study by Crill et al. (2004) provides some indication that participants will perform a Forward Lunge Test in a consistent manner.

Although the Forward Lunge is commonly used by many clinicians, and various forms of the test are included in several textbooks (Cook, 2003; Liebenson, 2007; Reiman & Manske, 2009), there is little consistency in how the Forward Lunge is administered. Furthermore, to the author's knowledge, there are no objective data regarding the reliability or validity of hip extension or APT measurements taken during the Forward Lunge Test. If the Forward Lunge is to be used as a clinical test to assess the degrees of hip extension and APT utilized to rotate the thigh posteriorly behind the body, a standardized procedure for administering the test must be established, and information regarding the validity and reliability of the test must be gathered.

2.5.4 Test Validity

The validity of a measurement refers to the extent to which the test measures what it is purported to measure (Gajdosik & Bohannon, 1987). Concurrent validity is a type of validity that involves correlating a measurement or test with some criterion that is administered at or about the same time (i.e. concurrently). Concurrent validity is usually used when one wants to substitute a shorter, more easily administered measurement procedure form one that is more difficult to administer or measure (Thomas et al., 2005).

Researchers typically validate measurements by comparing the measurement made with a new test or measurement procedure with the results obtained from the best accepted test or measurement procedure, known as a gold standard. A Bland-Altman plot (mean difference plot) comparing the difference between the two methods against the mean of the two measures is commonly used to determine validity of a measurement technique (Bland & Altman, 1986). The plot of differences against the mean also allows one to investigate any possible relationship between the measurement error and true value. The bias and level of agreement can then be summarised from the mean difference and standard deviation of the differences. It is generally expected that most differences will fall within two standard deviations of the difference in means (i.e. mean difference +/- (2 x standard deviation)). This provides the upper and lower limits of agreement (LOA). If differences between the measurements are small and unlikely affect clinical decisions the new method can be considered valid and the new measurement method can be used in place of the old. In practice, the amount of difference between the new and old methods that would be considered acceptable will vary and depend on the context in which the measurements are used.

Ecological validity is concerned with how closely the parameters of the research study approximate the real-life situation that is under investigation. In practical terms, ecological validity has been taken to refer to whether or not study findings observed in the laboratory can be generalized to behaviour in the natural world (Schmuckler, 2001). Ecological validity is most commonly discussed in reference to psychological research, and focuses on how factors such as experimental setting, the stimuli under investigation, and the observers response affect the outcome measures; however, the concept of ecological validity can be applied to other forms of testing and evaluation, including clinical testing. For example, with respect to ROM testing, clinicians commonly take patients through a series of tests which assess body segments in isolation from one another. However, this is not how joints move in the vast majority of real life tasks. Therefore, testing joint ROM in such an artificial, isolated fashion would be considered to have low ecological validity. As tests with higher ecological validity are presumably more desirable (assuming other critical criteria such as concurrent validity and reliability are met) it would be advantageous to develop tests that are more ecologically valid to be used in a clinical setting.

2.5.5 Test Reliability

Reliability refers to the consistency or repeatability of a measure (i.e. whether the application of the test produces the same measurements consistently over time under the same conditions) (Gajdosik & Bohannon, 1987). A reliable test is one that has small within-individual variation and a high test-retest correlation between repeated tests (Soper et al. 2004). Examiner reliability can be classified as either intra-rater (i.e. within examiner) or inter-rater (i.e. between examiner) (Peeler & Anderson, 2007). Perhaps the best measure of reliability for continuous data is the intra-class correlation coefficient (ICC). The ICC is a reliability coefficient that describes how strongly ratings agree with one another. ICC's are calculated using variance estimates obtained through an analysis of variance (ANOVA) (Portney & Watkins, 1993). In theory, the ICC is a ratio between the variance in the true scores over the sum of the true score variance plus variance due to error. This can be written as: $ICC = S^2_{True} / (S^2_{True} + S^2_{Error})$.

Shrout and Fleiss (1979) have described three different models of the ICC. These equations are dependent upon how raters are chosen. These models are further divided based on whether the analysis is conducted using single (individual) or averaged measures. Therefore, there are actually six different equations for calculating the ICC. According to the conventions described by Shrout and Fleiss (1979), when each subject is rated by the same rater, ICC model 3 should be used. When single measurements are used for data analysis, the ICC equation to be used would be $ICC(3,1) = (BMS-EMS)/(BMS + (k - 1)EMS)$ where BMS is the between-subjects mean score, EMS is the error mean score, and k is the number of measurements taken. When the mean of several measurements are used for analysis, the ICC equation to be used would be $ICC(3,k) = (BMS-EMS)/BMS$. Although reliability studies based on comparison of individual measurements are most common, in situations where measurements are unstable from trial to trial it may be necessary to base the analysis on the mean of several measurements. This has the effect of increasing reliability as means are considered better estimates of true scores (Portney & Watkins, 1993).

In situations in which subjects are tested or measured by several different raters, and these raters are assumed to be randomly selected, allowing results to be generalized to other raters, ICC model 2 is used. When single measurements are used for data analysis, the ICC equation to be used would be ICC(2,1) = (BMS-EMS)/((BMS + (*k* – 1)EMS) + ((*k*(RMS – EMS))/n), where RMS is the between-raters mean square. When the mean of several measurements are used for analysis, the ICC equation would be ICC(2,k) = (BMS-EMS)/(BMS + (RMS-EMS)/n).

Although there are no standard values for acceptable reliability using the ICC, as a general guideline Peeler and Anderson (2007) note that ICC values above 0.75 should be considered representative of high levels of reliability, while values between 0.4 and 0.75 should be considered representative of fair to moderate levels of reliability, and values below 0.4 are indicative of poor reliability.

The ICC is perhaps the most common method used to assess test reliability, however, since it is a ratio of variance between subjects to the total variance, the ICC reflects the ability of a test to differentiate between different subjects and does not provide an assessment of the trial-to-trial changes expected for an individual (Weir, 2005). This information is important for clinicians who monitor changes in individual patients. For example, to determine if a treatment intervention is having the intended effect clinicians need to know what degree of change represents a real change in performance. This information is provided by the standard error of measurement (SEM).

Unlike the ICC, which is a relative measure of reliability, the SEM is an absolute measure of reliability (Weir, 2005). Essentially, the SEM quantifies the precision of individual scores on a test. The SEM can be calculated by taking the square root of the mean square error term from the ANOVA. Confidence intervals can be calculated based on the SEM, which expresses the expected distribution of error around a measurement result (Roebroek, Harlaar, & Lankhorst, 1993). These confidence intervals indicate the smallest detectable difference between measurements than represent a real (non-error) change in performance.

2.5.6 Sources of Measurement Error

Measurement error can come from four sources: the participant, the testing procedure, the scoring, and the instrumentation (Thomas et al., 2005). Measurement error associated with the participant can include factors such as the physical state of the muscles and joints at the time of testing and familiarity with the test. To minimize these errors a standardized warm-up can be performed prior to testing in an attempt to have each participant in the same state of readiness, and practice trials can be performed to familiarize participants with the testing procedure. Additional factors such as mood and motivation may also contribute to measurement error (Thomas et al, 2005), however, these factors are more difficult to control.

Potential error associated with testing can include those due to a lack of standardization of the test procedures, difficulty in locating bony landmarks to be used as reference points, inconsistencies with marker location when testing on different occasions, and movement of markers over the skin/clothing. To minimize these errors during the proposed study as many aspects of the test procedure should be standardized in an attempt to have the participant move the same way during each trial. In addition, markers should be placed on participants by someone who is familiar with palpating the bony landmarks used to represent body segments.

Errors in scoring relate to the competence of the raters and the nature of the scoring itself (Thomas et al., 2005). These errors can be minimized by making the scoring as simple as possible, and ensuring the raters are well trained in how to measure the variables of interest. Finally, measurement error due to instrumentation includes inaccuracy of the measurement equipment resulting in poor data collection. To minimize this type of error equiptment should be properly calibrated and tested prior to data collection.

2.5.7 Validy and Reliability of the Optotrak Measurment System

The Optotrak is a research-grade motion capture system which uses optical lenses to capture the 3D position of infrared light-emitting diodes attached to specific anatomic landmarks. The motion of these diodes, which represent specific body segments, can then be numerically recorded and quantified using computer software. The Optotrak system has been shown to be highly accurate and reliable (Maletsky, Sun, & Morton, 2007; States & Pappas, 2006). When measuring the angle and position of markers adhered to a rigid body, States and Pappas (2006) found no significant differences in Optotrak measurements taken between days. Maletsky et al. (2007) found that for a typical operating set-up with the operating camera distance between 1.75 and 4.0 m, a 10 degree rotation showed a standard deviation in the measurements of 0.24 degrees, a bias (i.e., a systematic difference between an accepted reference value and a set of measured values) of 0.05 degrees and a 95% repeatability limit of 0.67 degrees. A 10 mm translation showed a standard deviation in the measurements of 0.10 mm, a bias error of 0.03 mm and a 95% repeatability limit of 0.29 mm.

Accuracy of the Optotrak will be affected by several factors, including distance between the markers and the camera, and the tilt of the markers relative to the cameras (States & Pappas., 2006; Maletsky et al., 2007). Gross human movements such as reaching, balance, and locomotion require a measurement volume of at least 1 m^3 to allow for limb motion. For the Optotrak, this requirement means its optical sensors must be configured to observe markers from a distance of 2 to 4 m from the sensors. The markers are designed to have a viewing angle of 120 degrees, meaning the marker can be detected as long as it is aligned to within 60 degrees of the plane of the sensors. States and Pappas (2006) found both precision and accuracy to decrease as the distance between the markers and sensors increased, although there were no significant differences in any measurements taken within the focal distances recommended by the manufacturer. Maletsky et al. (2007) also found the accuracy and repeatability decreased as camera distance increased and suggested to ensure accurate results care must be taken to keep the distance between the camera and markers within the limits suggested by the manufacturer.

2.5.8 Validity and Reliability of Photographic Measurement Techniques

To the author's knowledge, there are no studies reporting the validity or reliability of photographic measurements when measuring hip extension or APT, however photographic measurements have been shown to be valid and reliable when measuring other areas of the body. For example, for the lower extremity Moncrieff and Livingston (2009) reported moderate to high inter-rater reliability (ICC = 0.627 – 0.904) and intra-rater reliability (ICC = 0.700 – 0.839) when measuring tibiofemoral angles, and Mall, Hardaker, Nunley, and Queen (2007) reported photographic measurements to be reliable and valid when measuring foot posture (ICC = 0.557 - 0.992). For the upper extremity Hayes, Walton, Szomor, and Murrell (2001) reported fair to moderate inter-rater reliability (ICC = 0.62 – 0.73) and intra-rater reliability (ICC = 0.56-0.61) when measuring shoulder ROM using photographic images, and Niekerk, Louw, Vaughan, Grimmer-Somers, and Schreve (2007) found photographic measures of upper body seated posture to have moderate to high inter-tester reliability (ICC=0.78-0.99), and to be valid when compared with radiographic measures (r = 0.67-0.95).

With respect to photographic measurements one potential source of error relates to perspective, which refers to where the camera was positioned when the video/picture is taken. These errors can be minimized by keeping the camera level in the sagittal and frontal planes and positioned such that the camera lens is perpendicular to the plane of movement. In addition, the height of the camera can be adjusted to allow the camera to be as close as possible to the same height as the markers with the markers in the centre of the cameras visual field to minimize error due to lens distortion.

CHAPTER 3: METHODS

3.1 Sample

To determine concurrent validity, intra-rater reliability, and to determine the relationship between peak hip extension and peak APT during the Constrained Forward Lunge Test (CLFT) a sample of convenience consisting of 13 healthy runners (8 male, 5 female), with an average age of 47.6 years (range 34-65 years), average mass of 70.7 kg (range 54.6 – 109.1 kg), average height of 174.1 cm (range 160.0 – 193 cm) and average weekly running mileage of 42.6 km (range 25-80 km/week) was used.

To determine within-day inter-rater reliability a subset of 9 participants (5 male, 4 female) was used. The first 9 participants who were able to participate in the longer data collection session which was necessary for this portion of the study were chosen for this sample subset. This sample had an average age of 50 years (range 34-65 years), average mass of 72.6 kg (range 54.6 – 109.1 kg), average height of 170.1 cm (range 160.0 – 180.0 cm) and average weekly running mileage of 35.7 km (range 25-80 km/week).

To determine within-trial intra-rater and inter-rater reliability a subset of 10 participants (6 male, 4 female) was used. The first 10 participants were chosen for this sample subset. The sample had an average age of 43.2 years (range 34-59 years), average mass of 70.3 kg (range 54.6 – 75.0 kg), average height of 175.0 cm (range 160.0 – 193.0 cm) and average weekly running mileage of 43.1 km (range 25-80 km/week).

Runners were chosen as a sample population since one purpose of this proposed study was to determine if the measures of hip extension and APT taken during the CFLT approximate those seen during running. Although this comparison was made between the results obtained from this study and those reported in the literature, collecting data on participants that represent a similar sample population to those studied previously provides a more appropriate comparison. Furthermore, runners have been shown to display a wide variability in peak hip extension and APT during running, so it was anticipated that they would also display a wide variability in these variables during the CFLT. Variability in hip extension and APT measures is necessary to establish reliability using ICC's, and to establish a relationship between peak hip extension and peak APT during the CFLT, if such a relationship exists. Including both men and women in the sample was also done in an effort to increase the variability in the sample as women were expected to possess greater hip extension flexibility compared to male participants. Including both men and women in the sample will also make the results of the study applicable to both men and women.

Following approval from the Health Sciences Research Ethics Board of Dalhousie University, participants were recruited from local running clubs. To meet the study inclusion criteria the participants had to run on average a minimum of 24 km per week, and had to be 18 years of age or older. Exclusion criteria included any pain or injury in the right or left leg, hip, pelvis, or back that had prevented them from running or caused them to take a day off from their normal running schedule either at the time of testing or within in the past three months (see Appendix C for Participant Screening Script). These inclusion/exclusion criteria were similar to those used by previous studies measuring hip extension and APT during running (Franz et al., 2009; Schache et al., 2000, 2001, 2002).

3.2 Ethical Issues

All participants were informed via a written consent form and verbal explanation of possible detrimental effects resulting from participation in this study. It was also clearly explained to each participant that they had the right to withdraw from the study at anytime without consequences. All participants were given the opportunity to ask any questions regarding the informed consent or testing procedures.

Confidentiality and anonymity were ensured by assigning each participant an identification code. This code was then used for all data storage. The key matching participants to their respective identification codes was stored as a password protected file, with the password being known only to the Principal Investigator and the Study Advisor.

3.2.1 Potential risks of participating in this study

1) Minor skin irritations caused by the tape used to apply the markers to the participants skin.
2) Minor strains and muscle soreness from the lunge movement due to stretching and eccentric contractions of the lower extremity muscles, particularly the quadriceps, hip flexors, and hip extensor muscles. To minimize this risk, participants were not expected to endure pain or discomfort during data collection. Participants were instructed that if any pain or discomfort was felt they were to inform the examiner and the test would stop.

    Participants were tested in isolation from one another so they would not see other participants perform the Constrained Forward Lunge Test and would therefore not have any pre-conceived notions of how they are supposed to perform the test and would not try to copy other participants, which may have placed undue strain on their bodies. Finally, participants performed a warm-up consisting of walking on a treadmill to increase blood flow and flexibility of the lower extremity muscles prior to testing, which should have further reduced any injury risk. No participants reported any pain or discomfort during or after any of the testing sessions.

3) In addition, some participants, particularly women, may have felt uncomfortable with a male examiner locating bony landmarks and placing the markers on their hips and pelvis. To ensure that this was not an issue all participants were informed of the data collection process prior to data collection and were able to withdraw from the study if they were uncomfortable with this aspect of participation.

3.3 Standardization of Testing Procedure

To standardize the Constrained Forward Lunge Test (CFLT) for this investigation two lines were be made on the floor (Figure 4). One line was perpendicular to the wall to the left of the participant. This line was used to establish the starting position of the Constrained Forward Lunge and was referred to as the 'starting line.' The other line was parallel to the wall and perpendicular to the starting line, and was referred to as the 'step line.' To control (i.e., constrain) step length a large box was placed in front of the participant along the step line at a distance equal to their leg length, which was determined by measuring the distance between the floor and their right greater trochanter. Based on the principal investigator's clinical experience, along with the information gained through preliminary testing, using the height of the greater trochanter as the step length seemed appropriate as it allows the thigh to sufficiently rotate posteriorly past vertical to create hip extension without causing excessive effort or strain for the participant. Furthermore, this distance is quick and easy to measure, making it useful for clinicians.

Participants began in a relaxed standing position facing the box with their toes on the starting line. Each participant was then instructed to step forward with the left leg and bring their toes to the box while keeping both feet parallel to the step line. From this position he/she bent their left knee so that it was in contact with the box with the knee positioned directly over their toes. They were instructed to relax their right knee allowing it to bend towards the floor. Each participant performed the CFLT with their arms crossed over their chest to ensure all markers could be seen by the Optotrak system and camcorder (Figure 2). Between each lunge, participants were instructed to march in place for thirty seconds.

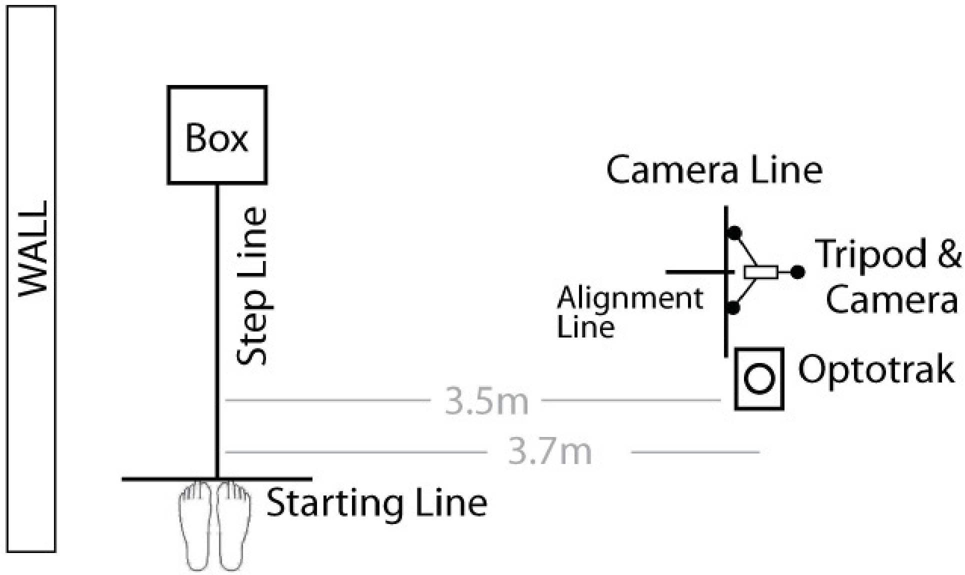

Figure 4. Diagrammatic representation of the testing area. Participants began with their toes positioned along the starting line. A large box was placed in front of the participant along the step line at a distance equal to their leg length as measured from the lateral malleolus to greater trochanter. The tripod was placed along the camera line and the camera lens was visually lined up so that it is pointing straight along the alignment line and perpendicular to the plane of the movement. During data collection the Optotrak system was positioned to the left and slightly behind the tripod/camera approximately four meters away from the participant.

To minimize errors due to perspective and to standardize the camera position a line was placed on the floor that was parallel to and approximately three and a half meters away from the step line. This is referred to as the camera line. A second line was placed perpendicularly through this camera line and positioned so that it lined up with the approximate position of the participants greater trochanter in the end position of the CFLT. This line is referred to as the alignment line. The tripod was placed along the camera line and the camera lens was visually lined up so that it is pointing straight along the alignment line and perpendicular to the plane of the movement. A spirit level was placed against the face of the camera to ensure there was no tilting of the camera lens. The height of the tripod was adjusted to allow the camera to be at the same height as a horizontal reference line drawn on the wall to the left of the participant, a line which served as a reference line for the photographic measurements. During data collection the Optotrak system was positioned to the left and slightly behind the tripod/camera three meters and 70 centimetres away from the participant. This distance is within the focal distance recommended by the Optotrak manufacturer.

For data collection, each complete Constrained Forward Lunge was captured by the camcorder and Optotrak system simultaneously. These data were used to determine the degrees of hip extension (HE) and anterior pelvic tilt (APT) demonstrated during the CFLT.

3.4 Measurement Instruments

3.4.1 Optotrak Kinematic Measurement System

To measure hip extension and APT three-dimensional coordinate data were collected at a sampling rate of 100 Hz using a single bank Optotrak Certus Motion Capture System (Northern Digital Inc., Waterloo, Canada). Prior to data collection the system was calibrated using a rigid 2-dimensional (x,y) orthogonal jig. The Optotrak system measurements served as the 'gold standard' for this study. To represent the pelvis Optotrak markers 2 cm in diameter were placed over the right anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS). To ensure the pelvic markers could be seen for the entire lunge movement the markers were attached to the base of small wands (6 cm in length), which were securely adhered to the ASIS and PSIS (Figure 2). The wands were attached either to compression shorts, or where possible, directly to the skin of each participant. To represent the thigh, markers were placed over the right greater trochanter and right lateral femoral condyle. The marker over the greater trochanter was adhered to compression shorts worn by the participants. The marker over the lateral femoral condyle was placed directly over the skin (Figure 2). Prior to data collection, test data were collected using this marker set up to verify that the Optotrak system was able to track all markers and that the markers placed over compression shorts stayed positioned over the anatomic landmarks during the forward lunge movement.

3.4.2 Optotrak Measurement Procedure

With each trial Optotrak system data were collected for 10 seconds. Participants were instructed to stand still for 3 seconds, lunge forward, and then hold the end CFLT position until the end of the data collection time frame. To obtain the required Optotrak data, the mean x and y positions of the markers attached to the ASIS, PSIS, greater trochanter, and lateral femoral condyle were calculated using the first and last 3 seconds of data. With known x and y coordinates, the APT angle (angle formed between a straight line connecting the ASIS and PSIS markers and horizontal) was calculated as the inverse tangent of the change in y (y_{ASIS}-y_{PSIS}) divided by the change in x (x_{ASIS}-x_{PSIS}). The thigh angle (the angle formed between a straight line connecting the greater trochanter and lateral femoral condyle markers and vertical) was calculated as the inverse tangent of the change in x ($x_{greater\ trochanter} - x_{lateral\ femoral\ condyle}$) divided by the change in y ($y_{greater\ trochanter} - y_{lateral\ femoral\ condyle}$). The hip extension (HE) angle was calculated by subtracting the thigh angle from the APT angle (Figure 5).

3.4.3 Photographic Measurement

Hip extension and APT was measured using a photographic assessment method. Each Constrained Forward Lunge Test was recorded with a high definition digital camcorder (Panasonic HD Everio GZ-HD3, Panasonic Corporation, Osaka, Japan) mounted on a tripod. This is a consumer grade camcorder and was chosen as it represents the type of camera clinicians could easily use in a clinical setting. The camera resolution was 1440 x 1080. Data was recorded at 30 frames per second with a shutter speed of 1/100. Optotrak markers used to represent the ASIS, PSIS, greater trochanter, and lateral femoral condyle, were also used to facilitate the photographic measurements (Figure 2). Preliminary data collection trials using this marker set up verified that all markers remained visible throughout the completion of the Constrained Forward Lunge Test and were easily identified when the still images were printed.

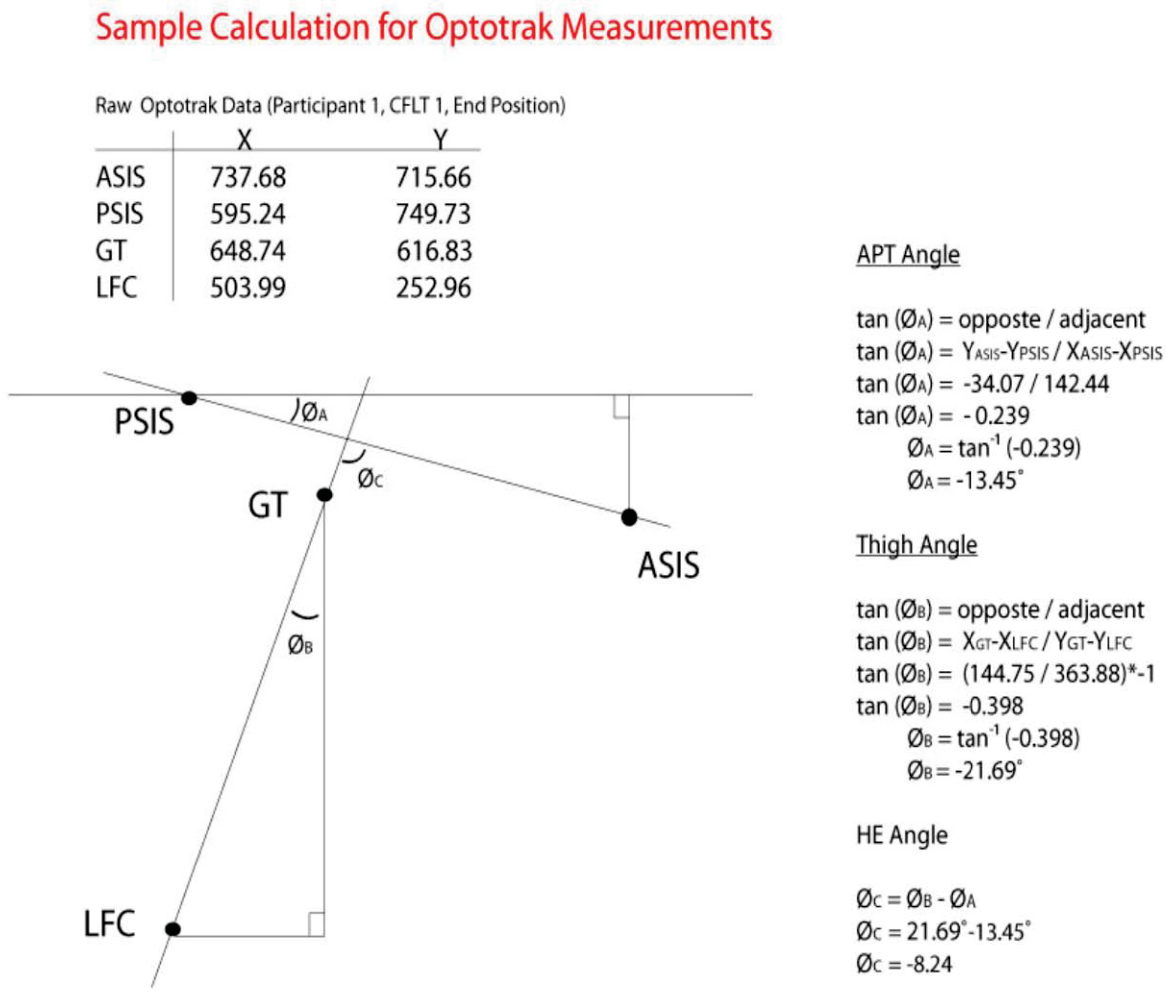

Figure 5. Sample Optotrak calculations for APT end, thigh end, and HE end positions during the CFLT. (ASIS = Anterior Superior Iliac Spine; PSIS = Posterior Superior Iliac Spine; GT = Greater Trochanter; LFC = Lateral Femoral Condyle).

3.4.4 Photographic Measurement Procedure

For photographic measurements a still picture of the start and end positions of the Constrained Forward Lunge Test were extracted from the digital video footage and used to measure the required anterior pelvic tilt (APT) and hip extension (HE) angles. The still pictures were printed in black and white using a Kodak ESP 9 inkjet printer (Kodak Conpany, Rochester, USA). The pictures were printed to a size of 13 x 18 cm and a resolution of 600 x 600 dpi. The examiners drew straight lines on each picture through the markers adhered to the ASIS and PSIS (pelvic line) and markers adhered to the greater trochanter and lateral femoral condyle (thigh line). A straight line was also drawn through a horizontal reference line which was placed on the wall behind the participants (Figure 6). A clear plastic protractor (Staedtler, Nuernberg,Germany) marked in one degree increments was used to measure the necessary angles. The anterior pelvic tilt (APT) angle was determined by measuring the angle formed between the pelvic line and horizontal, the thigh angle was determined by measuring the angle formed between the thigh line and vertical, and the hip extension (HE) angle was determined by measuring the angle formed between the pelvic line and the thigh line. All angles were measured in the starting position (relaxed standing) and in the end position of the CFLT. Range of motion (ROM) was determined by subtracting the respective end position angle form the start position angle.

3.5 Limitations

1) Marker placement for the gold standard differs from previous studies as the kinesiology lab has only a single bank of cameras. This different marker set-up may be a limitation when comparing the results of this study to those reported in the running literature.
2) All measures were made on the right side of the body. Although there may some asymmetries between the right and left sides, these asymmetries will not affect the validity or reliability of the measures of hip extension or APT.

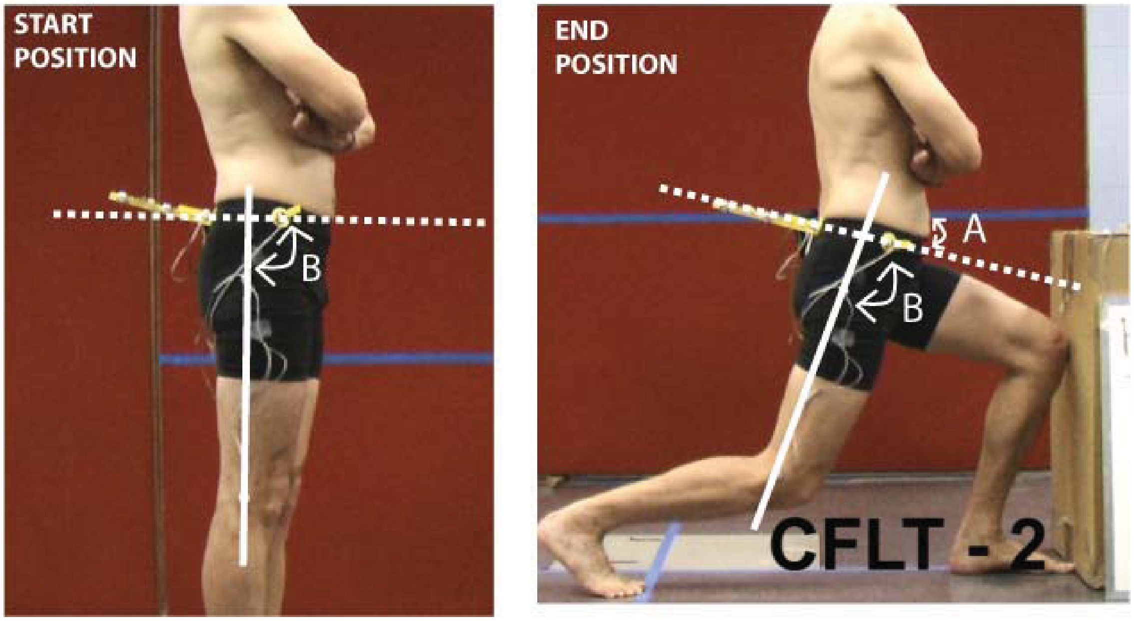

Figure 6. Photographic measurement procedure showing the APT reference line (dotted line) and Thigh reference line (solid line). These lines were drawn directly on the photographs by each examiner and used to measure APT, Thigh, and HE angles. 'A' represents the APT angle, measured as the angle formed between the Pelvic line and the horizontal reference line. 'B' represents the HE angle, measured as the angle formed between the Pelvic line and the Thigh Line.

3) Posterior rotation of the thigh behind the trunk occurs through motion of several anatomical segments (i.e., lumbar spine, pelvis, hip) and in multiple planes (i.e., sagittal, frontal, and transverse), however, this study will measure only sagittal plane motion at the hip and pelvis.

3.6 Procedure

All data collection took place within the Kinesiology laboratory facilities of Dalhousie University. Prior to data collection, written and verbal informed consent was sought. Data were obtained on two different days, up to seven days apart, to obtain test/re-test data.

3.6.1 Day 1 – Initial Data Collection

On the initial data collection day, following a review of the inclusion/exclusion criteria and informed consent, basic demographic information was collected. Participants then performed a warm-up consisting of walking at a self selected pace on a treadmill for 5 minutes. This warm-up was chosen to increase blood flow and flexibility of the lower extremity muscles, which was expected to help reduce the risk of injury. Furthermore, with the hip flexor muscles warmed up prior to testing it was expected to help reduce the between trial variability in hip extension and APT measures during testing. This warm up is the same as that used by Crill et al. (2004), who reported no injuries when collecting data on the Forward Lunge Test. Markers were then placed on the participants as described in the Measurement Instruments section by the principal investigator, JG, a licensed chiropractor familiar with palpation of the specified anatomic landmarks. Participants completed the Constrained Forward Lunge Test in bare feet. Prior to data collection each participant completed three Constrained Forward Lunge Tests (CFLTs) trials to familiarize themselves with the procedure. The participants then completed three Constrained Forward Lunge Tests to be used for data analysis. Following these three CFLTs, markers were removed and participants were then asked to return to the lab within seven days to obtain re-test data.

For a subset of nine participants the data collection procedure (including warm-up, marker-placement, trial CFLTs, and data collection CFLTs) was repeated by two additional examiners to obtain inter-rater reliability data. The two additional examiners were also licensed chiropractors and were familiar with palpating the above mentioned anatomic landmarks. To help ensure consistency in testing between examiners a thirty-minute training session was held prior to the initiation of data collection. The session consisted of a review of marker placement and testing procedures, including participant placement/positioning and instructions for performing the CFLT.

3.6.2 Day 2 – Data Collection Procedure for Re-Testing

To obtain the necessary re-test data participants returned to the Kinesiology laboratory within seven days of the initial testing. The testing procedure was the same as that for Day 1, with the exception of demographic data collection. Those participants who were part of the inter-rater reliability study and measured by all three examiners on Day 1 were measured only by the principal investigator on Day 2 of data collection.

3.7 Statistical Analysis

Statistical analyses were performed to determine the validity and reliability of hip extension and APT measurements taken during the CFLT.

3.7.1 Concurrent validity

Concurrent validity between the photographic and Optotrak measurements of HE ROM and APT ROM was analyzed using intraclass correlation coefficients (ICC(2,k)) and Bland-Altman plots. This was done by plotting the difference between photographic and Optotrak measurements against their means and calculating the systematic bias and random error (95% limits of agreement).

3.7.2 Intra-rater reliability

To determine the within trial, within-day, and between day test / re-test intra-rater reliability of hip extension and APT measures taken from the photographic images intraclass correlation coefficients ICC(3,1) and ICC(3,k) were calculated using repeated measures ANOVAs and the equation: ICC(3,1) = (BMS-EMS)/(BMS + (k - 1)EMS), where BMS is the between-subjects mean score, EMS is the error mean score, and k is the number of measurements taken. ICC(3,k) values for hip extension and APT measures were calculated separately using repeated measures ANOVAs and the equation: ICC(3,k) = (BMS-EMS)/BMS. In addition to ICC calculations, standard error of measurement (SEM) with confidence intervals were calculated to determine the precision of individual scores and the smallest detectable differences for between-trial and between-day intra-rater measurements.

3.7.3 Inter-rater reliability

To determine the within trial and within-day test / re-test inter-rater reliability of hip extension and APT measures taken from the photographic images intraclass correlation coefficients (ICC(2,1) and ICC(2,k)) were calculated. ICC(2,1) values for hip extension and APT measures were calculated using repeated measures ANOVAs and the equation: ICC(2,1) = (BMS-EMS)/BMS+(k-1)EMS+[k(RMS-EMS)/n, where BMS is the between-subjects mean square, EMS is the error mean square, RMS is the between-raters mean square, k is the number of raters, and n is the number of subjects tested. ICC(2,k) values for hip extension and APT measures were calculated using repeated measures ANOVAs and the equation: ICC(2,k) = (BMS-EMS)/BMS+(RMS-EMS)/n. In addition to ICC calculations, SEMs with confidence intervals were calculated to determine the precision of individual scores and smallest detectable differences for between-trial measurements for both individual and averaged measurements.

3.7.4 Relationship between hip extension and APT during the CFLT

To determine the relationship between hip extension and APT during the CFLT a correlational assessment will be performed. To conduct this analysis, Pearson Product Moment correlation coefficients were calculated and a simple linear regression was performed to determine the degree of association between the degrees of hip extension and APT utilized during the Forward Lunge. In this analysis, the predictor variable was hip extension as measured from the photographic images. The response variable was APT measured from the same images. Statistical significance for all tests was set at the $P < 0.05$ level.

3.7.5 Descriptive analysis

In addition to the statistical procedures described above, the photographic measures of hip extension and APT were compared on a descriptive level with the ranges of these measures as presented in the running biomechanics literature.

CHAPTER 4: RESULTS

Of all the variables measured in this study, anterior pelvic tilt range of motion (APT_{ROM}) and hip extension range of motion (HE_{ROM}) are the most important to clinicians. These variables reflect the contributions made by the pelvis and hip as the thigh rotates back behind the body. Furthermore, unlike using measurements of absolute angles, measures of ROM will be less affected by variability in the orientation of anatomic landmarks and marker placement from one test to another. For healthy adult runners performing a Constrained Forward Lunge Test (CFLT), mean values for APT_{ROM} and HE_{ROM} were 9.35 ± 3.92 degrees, and 11.21 ± 7.89 degrees respectively. The mean and standard deviations of additional variables measured can be found in Table 7.

Table 7. Summary of start position, end position, and range of motion measurements for the pelvis, hip, and thigh. Measurements are based on Day 1 data from Examiner 1.

	Pelvis			**Hip**			**Thigh**		
	Start (degrees)	**End** (degrees)	**ROM** (degrees)	**Start** (degrees)	**End** (degrees)	**ROM** (degrees)	**Start** (degrees)	**End** (degrees)	**ROM** (degrees)
Mean	-5.59	-14.94	9.35	3.28	-7.92	11.21	-2.23	-22.90	20.67
SD	4.37	4.62	3.92	5.14	8.67	7.89	3.25	7.26	5.80

4.1 Validity

Concurrent validity between photographic measurements of APT_{ROM} and HE_{ROM} and measures taken with the Optotrak system was analyzed using intraclass correlation coefficients (ICC(2,k)) and Bland-Altman plots. Intraclass correlation coefficient calculations were based on the differences between the mean of three photographic measurements and the mean of three Optotrak measurements. ICC(2,k) values were 0.94 for APT_{ROM} and 0.99 for HE_{ROM} (Table 8). With respect to the Bland-Altman analysis,

APT_{ROM} showed a bias of -1.42 degrees with a lower limit of agreement of -3.40 degrees and upper limit of agreement of 0.57 degrees, indicating that the photographic measurements had a tendency for greater APT_{ROM} measurements. HE_{ROM} demonstrated a bias of 0.41 degrees with a lower limit of agreement of -1.73 degrees and upper limit of agreement of 2.54 degrees (Table 8, Figures 7 and 8). Based on these calculations photographic measurements of APT_{ROM} and HE_{ROM} during the CFLT would be considered valid compared with Optotrak measurements.

Table 8. Concurrent validity of photographic measurements of APT_{ROM} and HE_{ROM} with Optotrak measurements during the CFLT in healthy adult runners.

	ICC(2,1)	**95% CI**	**LOA** (degrees)
APT ROM	**0.94**	**-3.40 to 0.57**	**-1.42 ± 1.99**
HE ROM	**0.99**	**-1.73 to 2.54**	**0.41 ± 2.13**

4.2 Reliability

4.2.1 Intra-Rater Reliability

Within-trial intra-rater reliability provides an isolated estimate of the reliability of the measurement technique with respect to measurements made by a single rater. This was determined by taking measurements of duplicate photographs and calculated using ICC(3,1). Based on this model, APT_{ROM} and HE_{ROM} had ICC(3,1) values of 0.92 and 0.94 respectively. ICC (3,1) values for APT start position, APT end position, hip extension start position, and hip extension end position also exhibited high reliability (Table 9). This data demonstrates that the measurement technique used to measure hip and pelvic angles from photographs taken from CFLTs are highly reliable.

Within-day intra-rater reliability, which was determined by comparing measurements from three consecutive trials, was also calculated using ICC(3,1). Based on this model, APT_{ROM} and HE_{ROM} had ICC(3,1) values of 0.64 and 0.89 respectively (Table 10). Between-day intra-rater reliability, which was determined by comparing

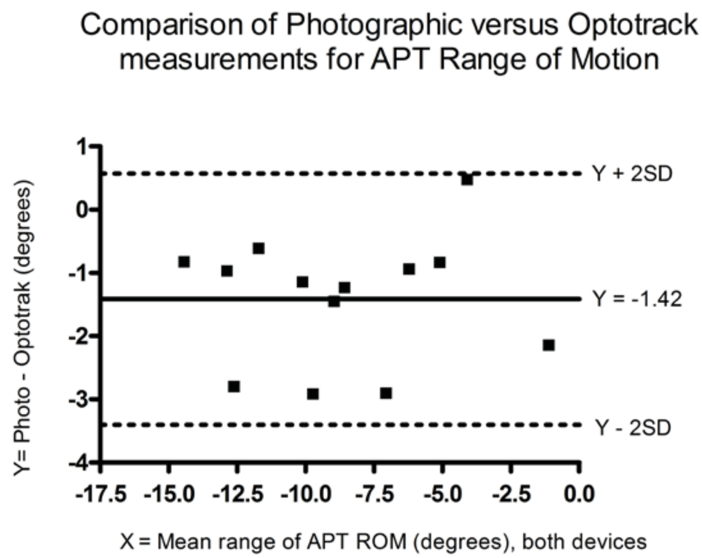

Figure 7. Bland-Altman plot comparing the difference between the two methods of measurements (Photographic measurements and Optotrak) versus the average of the two measurements for APT ROM. Systematic bias is represented by the solid line. LOA (±2SD) are given by the dotted lines.

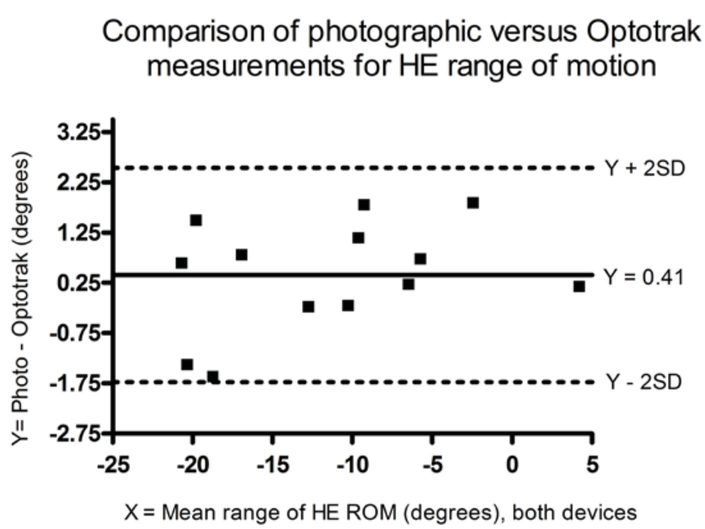

Figure 8. Bland-Altman plot comparing the difference between the two methods of measurements (Photographic measurements and Optotrak) versus the average of the two measurements for HE ROM. Systematic bias is represented by the solid line. LOA (±2SD) are given by the dotted lines.

Table 9. ICC values calculated from photographic measurements of the anterior pelvic tilt and hip extension taken from duplicate photographs by a single examiner (within-trial intra-rater reliability).

	ICC(3,1)
APT Start	0.88
APT End	0.95
APT ROM	0.92
HE Start	0.91
HE End	0.96
HE ROM	0.94

measurements on two separate days, was also calculated using ICC(3,1). ICC(3,1) values for APT_{ROM} and HE_{ROM} were 0.75 and 0.76 respectively (Table 11). In addition to calculating reliability using single measurements, between-day intra-rater reliability was also calculated using ICC(3,k), which compares the mean of several measures taken by the same examiner. When using the mean of three measurements, between-day intra-rater reliability of photographic measures of APT_{ROM} and HE_{ROM} had ICC(3,k) values of 0.91 and 0.80 respectively (Table 11).

Although there are no standard values for acceptable reliability using the ICC, as a general guideline, Peeler and Anderson (2007) suggest ICC values above 0.75 should be considered representative of high levels of reliability, while values between 0.4 and 0.75 should be considered representative of fair to moderate levels of reliability, and values below 0.4 are indicative of poor reliability. It appears that when using individual measurements, reliability of APT_{ROM} and HE_{ROM} is moderate to high. Using the mean of several measures has the effect of increasing the reliability coefficient. Therefore, when comparing measurements of APT_{ROM} and HE_{ROM} from one testing session to another, comparing the mean of several measurements is more reliable that using individual measurements.

Table 100. ICC values calculated from photographic measurements taken by the same examiner from three separate constrained forward lunge tests performed on the same occasion (within-day intra-rater reliability).

	ICC(3,1)
APT Start	0.94
APT End	0.75
APT ROM	0.64
HE Start	0.91
HE End	0.93
HE ROM	0.89
Thigh Start	0.88
Thigh End	0.92
Thigh ROM	0.85

In addition to APT_{ROM} and HE_{ROM}, ICC values for photographic measurements of the APT start position, APT end position, hip extension start position, hip extension end position, thigh start position, thigh end position, and thigh ROM were also calculated. A summary of the within-day intra-rater reliability calculations associated with these variables can be found in Table 10. Between-day intra-rater reliability calculations can be found in Table 11.

Table 11. ICC values calculated from photographic measurements of the pelvis, hip, and during the CFLT performed on separate days by the same examiner (between-day intra-rater reliability). (ICC(3,1) represents analysis based on individual measurements. ICC(3,k) represents analysis based on the mean of several measurements.)

	ICC(3,1) 3 measurements	ICC(3,1) 1 measurement	ICC (3,k) 2 measurements	ICC(3,k) 3 measurements
APT Start	0.72	0.80	0.76	0.75
APT End	0.72	0.80	0.79	0.80
APT ROM	0.75	0.89	0.87	0.91
HE Start	0.72	0.78	0.73	0.74
HE End	0.73	0.71	0.72	0.74
HE ROM	0.76	0.82	0.78	0.80
Thigh Start	0.79	0.84	0.82	0.86
Thigh End	0.72	0.74	0.71	0.74
Thigh ROM	0.68	0.77	0.70	0.71

4.2.2 Inter-Rater Reliability

Within-trial inter-rater reliability, which provides an isolated estimate of the reliability of the measurement technique in reference to multiple raters by comparing measurements made on duplicate photographs, was calculated using ICC(2,1). This model compares single measurements made by several examiners on the same group of subjects. Based on this model, APT_{ROM} and HE_{ROM} had ICC(2,1) values of 0.96 and 0.98. ICC (2,1) values for APT start position, APT end position, hip extension start position, and hip extension end position also exhibited high reliability (Table 12). These data demonstrate that the measurement technique used to measure hip and pelvic angles from photographs taken from CFLTs is highly reliable across multiple raters.

Within-day inter-rater reliability was calculated using ICC(2,1). Based on this model, APT_{ROM} and HE_{ROM} had ICC(2,1) values of 0.86 and 0.90 respectively (Table 13). In addition to calculating reliability using single measurements, reliability was also calculated using ICC(2,k), which compares the mean of multiple measurements made by one examiner with the mean of multiple measurements made by other examiners.

Within-day inter-rater reliability of photographic measures of APT_{ROM} and HE_{ROM} had ICC(2,k) values of 0.88 and 0.89 respectively (Table 13). It appears that when using individual measurements, reliability of PT_{ROM} and HE_{ROM} is high. Using the mean of several measures does not appear to consistently increase the reliability coefficient of these variables.

In addition to APT_{ROM} and HE_{ROM}, ICC (2,1) and ICC(2,k) values were also calculated for APT start position, APT end position, hip extension start position, hip extension end position, thigh start position, thigh end position, and thigh ROM. A summary of these calculations can be found in Table 13.

4.2.3 Number of measurements required

Originally, the ICC(3,k) and ICC(2,k) calculations were based on an average of three measurements, which, as outlined above, demonstrated high levels of both intra-rater and inter-rater reliability. From a clinical perspective, it is also important to know how many measurements must be taken to ensure a high level of reliability. Therefore, for between day intra-rater reliability, in addition to calculating ICC(3,k) values based on the mean of three measurements taken from each testing session, ICC values were also calculated using single measurements as well as the mean of the first two measurements taken for each day of testing. Using just the first measurement taken on each testing day resulted in ICC(3,1) values of 0.89 for APT_{ROM} and 0.82 for HE_{ROM}. Using the mean of the first two measurements taken on each testing day resulted in ICC(3,k) values of 0.87 for APT_{ROM} and 0.78 for HE_{ROM} (Table 11). Based on these calculations there does not appear to be any notable increase in ICC values based on using a single measurement, the mean of two measurements, or the mean of three measurements (Figure 9).

For within-day inter-rater reliability, in addition to calculating ICC(2,k) values based on the mean of three measurements taken by each rater, ICC values were also calculated using single measurements as well as the mean of the first two measurement taken for each rater. Using just the first measurement resulted in ICC(2,1) values of 0.68 for PT_{ROM} and 0.66 for HE_{ROM}. Using the mean of the first two measurements taken on each testing day resulted in ICC(2,k) values of 0.84 for PT_{ROM} and 0.86 for HE_{ROM} (Table

Table 12. ICC values calculated from photographic measurements taken from duplicate photographs by a three different examiners (within-trial inter-rater reliability).

	ICC(2,1)
APT Start	0.96
APT End	0.98
APT ROM	0.96
HE Start	0.97
HE End	0.98
HE ROM	0.98

Table 13. ICC values calculated from photographic measurements of pelvis, hip, and thigh taken by three different examiners during the constrained forward lunge test performed on the same occasion (within-day inter-rater reliability). (ICC(2,1) represents analysis based on individual measurements. ICC(2,k) represents analysis based on the mean of several measurements.)

	ICC(2,1) 3 measurements	**ICC(2,1) 1 measurement**	**ICC (2,k) 2 measurements**	**ICC(2,k) 3 measurements**
APT Start	0.76	0.39	0.66	0.69
APT End	0.68	0.41	0.61	0.60
APT ROM	0.86	0.68	0.84	0.88
HE Start	0.80	0.45	0.73	0.74
HE End	0.86	0.56	0.81	0.82
HE ROM	0.90	0.66	0.86	0.89
Thigh Start	0.78	0.46	0.73	0.73
Thigh End	0.87	0.65	0.94	0.83
Thigh ROM	0.85	0.57	0.81	0.82

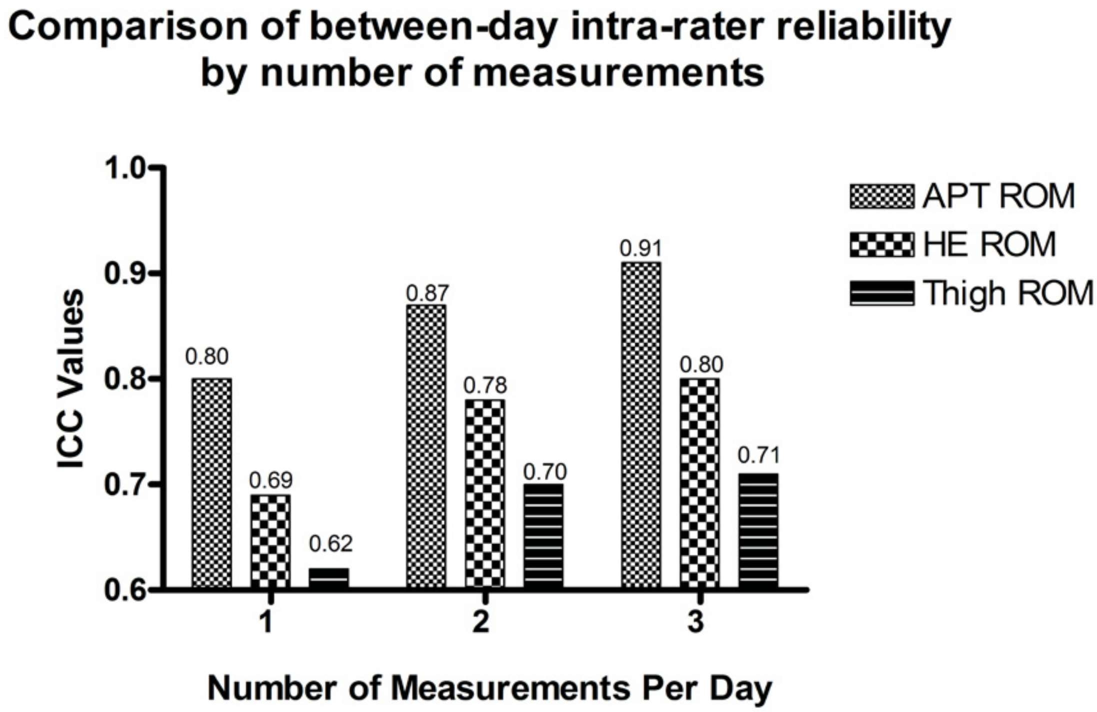

Figure 9. Comparison of ICC values based on the number of measurements taken per testing session by a single rater. There does not appear to be any notable increase in ICC values based on using a single measurement, the mean of two measurements, or the mean of three measurements.

13). Based on these calculations it appears that with respect to inter-rater reliability, using the mean of several measurements is more reliable that using single measurements, however, using the mean of three measures is only marginally more reliable that using two measurements (Figure 10).

4.2.4 Standard Error of Measurement (SEM)

The standard error of measurement (SEM) corresponding to measurements made by a single rater are provided in Table 14. With respect to measurements taken from 3 consecutive trials on the same day, the SEM for APT_{ROM} was 2.70 degrees, and for HE_{ROM} was 2.75 degrees. For measurements taken from 3 consecutive trials on two separate days, the SEMs for APT_{ROM} and HE_{ROM} are 2.85 degrees and 4.63 degrees

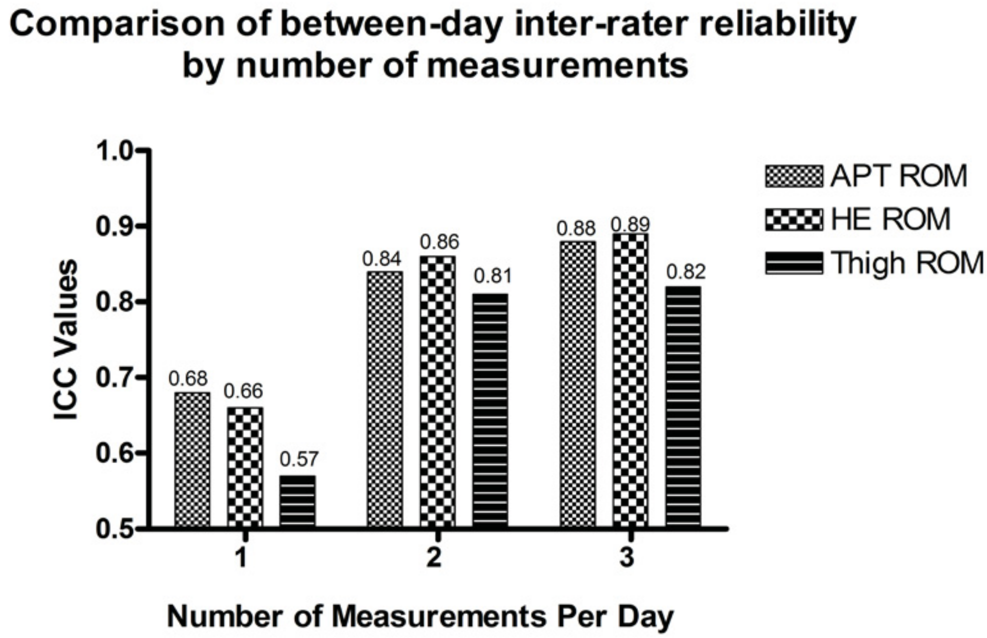

Figure 10. Comparison of ICC values based on the number of measurements taken per testing session for multiple raters. Using the mean of several measures does not appear to consistently increase the reliability coefficient of these variables, however using only one measurement seems to result in much lower reliability

respectively. When using the mean of three measurements from two separate days, the SEMs for APT_{ROM} and HE_{ROM} were 2.10 degrees and 5.32 degrees. These SEM values increased slightly to 2.52 degrees for APT_{ROM} and 5.65 degrees for HE_{ROM} when using the mean of only 2 measurements.

To aid in the interpretation of measurement results into clinical practice the smallest detectable difference (SDD) for each measurement (95% confidence interval corresponding to each SEM measurement) is also provided in Table 14. The SDD shows that with respect to photographic measurements of APT_{ROM} and HE_{ROM} taken during the CFLT in healthy adult runners, when measurements are taken by the same examiner on different days, a minimum change of 4.12 degrees for APT_{ROM} and 10.43 degrees for

HE_{ROM} is needed to be confident that the changes seen between testing sessions are real changes. This is assuming the mean of three measurements are used in calculating the associated pelvic and hip angles. If individual measurements are used, only changes in APT_{ROM} larger than 5.59 degrees, and changes in HE_{ROM} larger than 9.08 degrees can be interpreted as real changes.

The SEMs corresponding to measurements made by a three different raters within the same day are provided in Table 15. For measurements taken from 3 consecutive trials on the same day, the SEMs for APT_{ROM} and HE_{ROM} were 3.34 degrees and 4.94 degrees respectively. When using the mean of three measurements, the SEMs for APT_{ROM} and HE_{ROM} were 2.95 degrees and 4.97 degrees respectively. These SEM values increased slightly to 3.28 degrees for APT_{ROM} and 5.60 degrees for HE_{ROM} when using the mean of only 2 measurements.

4.3 Relationship between Pelvic Tilt and Hip Extension

To determine the relationship between the degrees of HE_{END} (peak hip extension) and APT_{END} (peak anterior pelvic tilt) utilized during the CFLT a Pearson Product Moment correlation coefficient was calculated and a simple linear regression was performed. In this analysis, the predictor variable was HE_{END} as measured from the hip angle from the photographic images in the end position of the CFLT. The response variable was APT_{END} measured from the same images. APT_{END} was shown to have a inverse correlation with HE_{END} during the CFLT, with a correlation coefficient of -0.54 and an r^2 value of 0.30 (y=-0.3x-17, 95% CI -0.46 to -0.14), however this correlation was not statistically significant (p=0.06) (Figure 9, solid line and filled circles).

Table 14. Standard error of measure and smallest detectable difference values for photographic measurements of anterior pelvic tilt range and hip extension range of motion taken by a single examiner.

	SEM (individual measurements)	**SDD**	**SEM (mean of 3 measurements)**	**SDD**	**SEM (mean of 2 measurements)**	**SDD**
APT ROM						
Within-Trial	1.39	2.71	-	-	-	-
Within-Day	2.70	5.29	-	-	-	-
Between-Day	2.85	5.59	2.10	4.12	2.52	4.94
HE ROM						
Within-Trial	1.73	3.38	-	-	-	-
Within-Day	2.75	5.39	-	-	-	-
Between-Day	4.63	9.08	5.32	10.43	5.65	11.08

Table 15. Standard error of measure and smallest detectable difference values for photographic measurements of anterior pelvic tilt range and hip extension range of motion taken by a three different examiners.

	SEM (individual measurements)	**SDD**	**SEM (mean of 3 measurements)**	**SDD**	**SEM (mean of 2 measurements)**	**SDD**
APT ROM						
Within-Trial	1.26	2.47	-	-	-	-
Within-Day	3.34	6.54	2.95	5.78	3.28	6.44
HE ROM						
Within-Trial	1.81	3.55	-	-	-	-
Within-Day	4.94	9.69	4.97	9.74	5.60	10.98

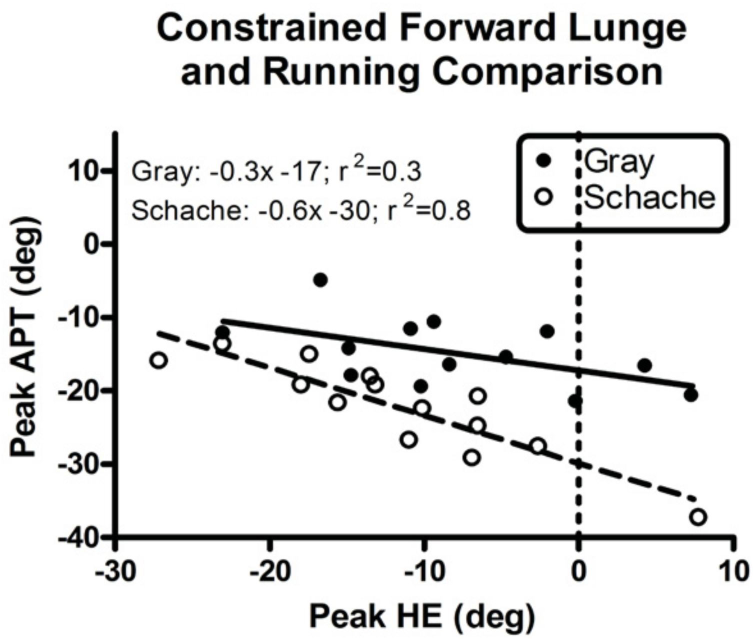

Figure 11. Comparison of the relationship between peak HE and peak APT during the CFLT to that seen during running. Constrained Forward Lunge Test and RunningThe solid line/filled circles represents the inverse relationship between peak anterior pelvic tilt and peak hip extension during the Constrained Forward Lunge Test. The broken line/empty circles represents a similar relationship between peak anterior pelvic tilt and peak hip extension during running as reported by Schache et al., 2000.

CHAPTER 5: DISCUSSION

5.1 Validity and Reliability

5.1.1 ICC and SDD Interpretation

The ICC represents a ratio of the true score variance, estimated by the variability in observed pelvic or hip measurement between subjects, over the sum of the observed score plus error. In other words, ICC calculations represent the proportion of variance attributable to the true score variance. For example, for an ICC value of 0.90 it can be concluded that approximately 90% of observed score variance is due to true score variance, while 10% is attributed to error.

As a general guideline Peeler and Anderson (2007) suggest ICC values above 0.75 should be considered representative of high levels of reliability, while values between 0.4 and 0.75 should be considered representative of fair to moderate levels of reliability, and values below 0.4 are indicative of poor reliability. Measures of APT_{ROM} and HE_{ROM} consistently demonstrated high reliability, with ICC values of 0.75 or greater for both within-day and between-day intra-rater reliability. Similar results we found with within-day inter-rater reliability. The only exception to this was seen with measures of within-day intra-rater reliability for APT_{ROM}, which had a ICC(3,1) value of 0.64. This would be indicative of a moderate level of reliability. Based on these results it would appear that photographic measures of APT_{ROM} and HE_{ROM} during the CFLT are reliable, however, one must be careful in how s/he interprets this information and applies it clinically. More specifically, it should be emphasized that the ICC normalizes the measurement error relative to the heterogeneity of the study population. This makes the ICC a relative measure of reliability that is able to differentiate between individuals; however, it does not provide an index of the expected trial-to-trial noise in the data (Weir, 2005).

This information is important for clinicians who monitor changes in individual patients. For example, to determine if a treatment intervention is having the intended effect, clinicians need to know what degree of change from test to test represents a real change in performance. This information is provided by the SEM and the smallest detectable difference (SDD). In practical terms, only changes larger than the SDD associated with a given measure can be interpreted as real change. Changes less than that may be due to other factors, such as measurement error or biological variability.

When comparing measurements taken by the same examiner on separate occasions (between-day) the SDD for APT_{ROM} ranged from 4.12 to 5.59 depending on whether one is comparing individual measurements or the mean on several measurements. For HE_{ROM}, the SDD ranged from 9.08 to 11.08. Therefore, in cases where a change in pelvic tilt or hip extension range of motion is a desired goal of treatment, a minimum change of 4.12 degrees in APT_{ROM} and 9.08 degrees in HE_{ROM} is needed between tests to be sure that the change is in fact due to the treatment intervention.

Although the SDD's associated with the CFLT may seem high they are comparable to SDD's reported in reference to other common clinical tests. For example, with respect to the Modified Thomas Test, Clapis et al. (2008) reported a SDD of 3.72 degrees when using a goniometer to measure hip extension. Peeler and Anderson (2008) found a SDD of 13.78 degrees when measuring knee flexion. In reference to other clinical measurements of the hip, Nussbaumer et al. (2010) reported SDD's of 7.72 for flexion, 4.63 for abduction and abduction, 4.74 for internal rotation, and 4.96 for external rotation.

5.1.2 Sources of error

As previously discussed, the ICC represents a ratio of the true score variance over the sum of the observed score plus error. The sources of error depend on the experimental design as well as which ICC model is used. For example, between-day intra-rater reliability was calculated using ICC model 3. Model 3 is a 2-way fixed effects model which considers only random error, including variance due to residual error and interaction between rows and columns in the error variance. Since raters are assumed to be fixed, column variance (i.e. systematic error) is excluded from the error term. Systematic error is considered an irrelevant source of variance when there is only a single rater of interest (McGraw & Wong 1996). In practical terms, with respect to the experimental design used for within-day intra-rater reliability, sources of error include biological variability (actual differences in pelvic or hip motion from trial to trial) and measurement error. Measurement error would include factors such as inaccuracies in how lines used to represent the hip and pelvis were drawn on the photographs and/or in how these lines were measured. For between day intra-rater reliability changes in marker placement form one testing session to another, as well as potential inconsistencies in camera alignment would be additional potential sources of measurement error.

Inter-rater reliability was calculated using ICC model 2. Model 2 is a 2-way random-effects model which considers both random and systematic error in its calculations. In this model, the error term includes variance due to random error, interaction, and columns (i.e. trial and/or raters). With respect to the experimental design used in determining inter-rater reliability, sources of error include biological variability and measurement error. Measurement error would include factors such as inaccuracies in how lines used to represent the hip and pelvis were drawn on the photographs, in how these lines were measured, and in differences in marker placement between raters.

As seen in Table 14, the SDD's for both APT ROM and HE ROM went from smallest to largest when comparing within-trial, between-trial, and between day measurements. This effect occurs because there are more sources of error for each successive measurement. For example, because the within-trial measurements consisted of measuring duplicate photographs, the only source of error was the measurement technique itself (i.e. drawing and measuring lines on each photograph). In addition to the error associated with the measurement technique, biological variability is an added source of error associated with the between-trial measurements. Finally, for the between day measurements, marker placement and camera positioning were additional sources of error on top of those associated with measurement technique and biological variability

5.1.3 Reducing Variability

As demonstrated by the generally high ICC values, photograph measurements of pelvic tilt and hip extension range of motion during the Constrained Forward Lunge Test appear to be reliable in the sense that measurements agree with one another. However, as indicated by the SEM and smallest detectable difference calculations, these measurements are not very sensitive to changes in pelvic and hip range of motion. The reason for this lack of sensitivity is related to the large trial-to-trial variability in APT and HE measurements. For APT_{ROM} same subject differences from trial to trial ranged from 1.0 to 4.0 degrees, with a mean standard deviation of 2.5 degrees. Similar results were seen with peak APT, peak HE, and HE ROM as well (see Tables D.11, D.15, D.23, and D.27 in Appendix D).. Although this may not seem like a large degree of variability from a clinical perspective, it is close to a quarter of the mean ROM seen across subjects (mean APT ROM = 9.35 degrees; HE ROM = 11.21 degrees).

To make the CFLT more sensitive to smaller changes in pelvic and hip motion less trial-to-trial variability is needed. With the experimental design, only the position of the lead knee was standardized. With respect to the trail leg, participants were instructed simply to let the trail leg bend and fall towards the floor. As previously discussed, this lack of standardization of the trail leg appeared to be a large source of variability, particularly with respect to the thigh and hip extension measurements. Standardizing the position of the trail knee would likely reduce some of the trial-to-trial variability. However, despite the expected improvement in sensitivity, standardizing the position of the trail leg may not necessarily improve the test as it makes the movement more artificial. One argument for using a lunge movement to assess pelvic and hip motion is that it may provide a better assessment of the natural segmental movement patterns associated with the thigh extending behind the body. Some variability in pelvic and hip motion during this movement pattern is expected, perhaps even desirable.

Based on the various ICC calculations, photographic measures of APT_{ROM} and HE_{ROM} appear to be reliable, at least in the sense that measurements taken by different examiners and by the same examiner on different occasions agree with one another. However, due to the relatively high SEM and smallest detectable differences associated with APT and HE measurements taken during the CFLT, one must be careful in how this test is used and interpreted in clinical settings. Due to the low sensitivity to changes in APT or HE ranges, the CFLT may not be the best test to monitor changes in these variables in response to treatment as a large change in performance in needed to represent real change.

5.2 Normative Data and Comparison to the ROM Measurement Literature

One objective of this study was to provide normative values for hip and pelvic motion during the CFLT. These data can be seen in Table 7. The mean APT_{ROM} of 9.3 degrees measured during the CFLT is slightly less than the standing active anterior pelvic tilt ROM of 12.56 to 12.86 reported by Gajdosik et al. (1985). The mean peak HE value of -7.9 degrees measured during the CFLT is less than the mean peak HE angle of -17.4 degrees measured during the Modified Thomas Test by Schache et al. (2000).

Although hip joint motion occurs as a result of movement of the thigh relative to the pelvis traditional measurement approaches rarely use the pelvis as a reference point during standard testing procedures. Instead, most tests measure the position of the thigh relative to the horizontal or relative to the midline of the trunk. With respect to hip extension the two most common tests used in clinical practice are prone hip extension and the Modified Thomas Test. Neither of these tests use the pelvis as a reference point. This is a problem as without directly measuring the position of the thigh relative to the pelvis the resulting thigh angle measurement will represent a combination of both thigh and pelvic motion, and will not provide an accurate measure of hip joint extension. Furthermore, since the trunk is flexible and is able to rotate and bend backwards or forwards, it is difficult to ensure the position of the trunk is consistent across subjects or remains consistent from one test to another.

Another potential problem with prone hip extension and the Modified Thomas Test is that they test the hip in an unloaded, open kinetic chain position. However, in functional activities such as walking and running hip extension occurs in a loaded, closed kinetic chain position. It is likely that the hip will behave differently between loaded and unloaded positions. As a result, assessing hip extension in a loaded position, and using the pelvis and thigh as reference points would likely provide valuable information to clinicians.

5.2.1 Comparison to the Running Literature

The mean APT_{ROM} of 9.3 degrees measured during the CFLT compares favourably with three dimensional data reported during running, with Schache et al. (2002; 2003), and Whittle et al. (2000) reporting APT ROM values of 7.8 to 9.4 degrees and 7.6 degrees, and 8.9 degrees, respectively. The average peak APT value of -14.9 degrees measured during the CFLT falls slightly below the typical 16.2 to 22.1 degree ranges reported in the running literature (Franz et al., 2009; Schache et al., 2000; 2001; 2002; 2003).

The mean peak HE value of -7.9 degrees falls on the lower end of what is reported in the running literature, which ranges from -5 to -20.5 degrees (Franz et al., 2009; Ounpuu, 1990; Pink et al, 1994; Schache et al., 2000, 2001, 2002, 2003). As there appears to be a trend in the running literature in which larger peak hip extension values occur in studies utilizing faster running speeds, it is possible that the magnitude of peak HE measured during the performance of a CFLT in this study may be more reflective of the degree of HE utilized at slower speeds. Further research would be needed to explore this notion.

The inverse relationship between peak HE and peak APT demonstrated during the CFLT is similar, albeit weaker, to that reported by Schache et al. (2000) during running ($y=-0.6x-30$, 95% CI -0.86 to -0.45, $r^2 = 0.80$) (Figure 11, broken line with empty circles).When comparing the relationship seen in the current study to that of Schache et al. (2000) two major differences can be seen (Figure 11). First, there is an offset in the regression lines demonstrating greater magnitudes of peak APT during running compared to the CFLT. This is most likely explained by the fact that during running the trunk and pelvis adopt a forward lean, especially at faster running speeds. This forward inclination would be expected to result in greater maximum and minimum APT angles without increases in the amplitude of pelvic tilt (i.e. APT_{ROM}) (Novacheck, 1999). This forward inclination of the trunk and pelvis was not typically seen in the CFLT as participants tended to adopt a more upright posture. As Schache et al. (2000) studied a sample of elite runners at a fairly fast running speed of 20 km/h (5.56 m/s) it seems reasonable to assume that a forward inclination of the trunk and pelvis during running could account for the offset in the regression lines.

Second, the slope of the regression line is steeper for running, suggesting that with lower magnitudes of peak hip extension greater APT occurs in running compared to the CFLT. With both running and the CFLT, an anterior pelvic tilt moment is created as the thigh rotates back behind the body and tension develops in the hip flexor muscles and anterior hip capsule. With the CFLT, it is expected that part of this anterior pelvic tilt moment would be offset by the posterior pelvic tilt moment created by the posterior hip muscles such as the gluteus maximus and hamstrings, and by the ground reaction force associated with the lead leg. In contrast, as peak HE and APT occur during running the contralateral leg is still in swing phase and would provide less resistance to the anterior pelvic tilt moment generated by the trail leg.

5.2.2 Comparison of the CFLT to the Modified Thomas Test

The modified Thomas Test is perhaps the most common method used to assess hip extension in a clinical setting; however, previous studies have failed to find a relationship between hip extension as measured during the modified Thomas Test and the degrees of hip extension or APT that occurs during running (Schache et al., 2000). The CFLT appears to be a good candidate to replace (or at least supplement) the Modified Thomas Test with a running population, not only because of factors presented above (i.e. favourable ICC/SEM values, the inverse relationship between peak hip extension and peak APT similar to that seen during running, and HE and APT values during the CFLT are similar to those presented in the running literature), but also because the CFLT may be more ecologically valid. For example, during running hip extension and APT motion occur as the thigh extends back behind the body during the push off phase of the stride. During this motion the body is upright, the stance hip is in a loaded position, and the trunk and pelvis are unrestricted. This is considerably different than the Modified Thomas Test which utilizes a supine, unloaded position with the trunk and pelvis stabilized by the position of the contralateral leg and the examination table. However, the position of the trail leg during the CFL more closely matches the position of peak hip extension and APT during running (i.e. the trail leg is posterior to the upright trunk and pelvis, the hip is loaded, and the trunk and pelvis are unrestricted). Furthermore the Modified Thomas Test is a test of passive flexibility, whereas the CFLT is an assessment of active flexibility, which again, is more consistent with how the hip extends during running.

Another favourable attribute of the CFLT is that is provides an opportunity to measure APT and hip extension concurrently, whereas the Modified Thomas Test allows one to measure only hip extension. Furthermore, the degrees of both APT and hip extension can be easily quantified with the CFLT, whereas the Modified Thomas Test is typically graded as pass/fail (as stated above, even if the Modified Thomas Test is quantified it is not a true measure hip motion as it does not measure the position of the thigh with respect to the pelvis). Quantification of joint range of motion has the advantage of allowing the clinician to more closely monitor a patient's response to treatment. This is more difficult to do under a pass/fail grading system as increases in range of motion are not recognized from test to test until the change becomes enough to evoke a change in the pass/fail classification.

It should be pointed out that although it appears that the CFLT is more ecologically valid, and the ranges of hip extension and APT appear similar to that seem during running, further research is need to determine if in fact the CFLT is able to provide an accurate assessment of hip and pelvic motion as it occurs during running.

5.3 Study Limitations

Although some version of a Forward Lunge Test is commonly used by many clinicians, the current study utilized a Constrained Forward Lunge Test (CFLT) which standardized the step length and lead leg position. Due to this standardization, results from the current study should not be assumed to hold true for other versions of the forward lunge test as constraining the lunge motion may result in different movement patterns, or at least different end range positions of the pelvis and thigh. In particular, constraining the step length may prevent the participant from reaching their maximum limit of hip extension and/or APT motion. In contrast, when performing an unconstrained lunge movement one would be more likely to reach their maximum limits of hip and pelvic motion as their forward motion is not prematurely stopped.

It is also possible that a greater step length associated with an unconstrained lunge would result in greater APT motion but not necessarily greater hip extension. For example, it is often assumed that sagittal plane rotation of the thigh behind the body occurs primarily with hip extension, then as the hip flexor muscles and anterior hip become tight, the pelvis begins to tilt anteriorly. If this is the case one could expect that even with a CFLT the hip may reach a position of maximum extension. However, to the authors' knowledge it is unknown whether posterior thigh rotation does in fact occur with this pattern of hip extension followed by APT. Further research is needed to clarify this notion.

While the CFLT may not necessarily provide an accurate assessment of maximum HE and APT ranges, this does not affect the potential value of the test as the goal is not so much to measure peak range capacity, but rather to assess how the participant is utilizing pelvis and hip motion to get the thigh behind the body. While maximum HE and APT capacity is certainly an important factor, other factors such as lumbo-pelvic-hip muscle balance and motor control/coordination are also factors that should be considered. Therefore, when abnormalities are seen during the CFLT other tests should be used (i.e., passive ROM testing, strength/motor control assessment, etc) to further investigate these factors to further determine why these abnormalities exist.

It should be recognized that posterior rotation of the thigh behind the trunk occurs through motion of several anatomical segments (i.e., lumbar spine, pelvis, and hip) and in multiple planes (i.e., sagittal, frontal, and transverse), however, this study measured only sagittal plane motion at the hip and pelvis. While increased APT is believed to be a common compensation pattern associated used to rotate the thigh back behind the body when hip extension capacity is restricted, it is expected that compensatory motions in other planes would also occur.

The generalizability of the results of the current study are limited to data gathered from healthy, adult runners. Further study is required to determine if similar results hold true for additional populations, including non-runners and injured individuals.

5.4 Future Directions

As discussed, previous studies have failed to find a significant relationship between measures of static hip extension flexibility and dynamic hip or pelvic motion during running (Schache et al. 2000) or walking (Lee et al., 1997). Given that peak HE and APT_{ROM} measured with the CFLT are similar to that seen during running and peak APT approaches the lower ranges seen with running, along with the similar relationship between peak HE and peak APT in both the CFLT and running, it is reasonable to assume that the CFLT would be an effective tool in helping clinicians to identify restricted or abnormal hip and pelvic motions in runners. However, this assumption is based on a comparison of the results of the current study with the existing running literature. Future research comparing hip and pelvic measures in the CFLT with that seen during running in the same subjects would be a logical next step to determine if in fact the hip and pelvic motion during the CFLT is representative of that seen during running. Additionally, it would also be helpful to study the CFLT in conjunction with other common clinical tests of hip extension flexibility to see if participants who demonstrated reduced hip extension flexibility during isolated ROM testing, such as the Modified Thomas Test, also demonstrated this same pattern during the CFLT.

Measurements in the current study are based on data collected from the start and end positions of the CFLT, however, it provides no information as to how this motion occurs. As opposed to looking at just the start and end lunge positions it would be valuable to study the entire lunge movement with an Optorak or other advanced motion capture system to see if there are consistent patterns of dynamic motion that occur. For example, does posterior thigh rotation occur first from the hip with the pelvis tilting anteriorly as the limit of hip extension is reached? Does the pelvis move first? Do the hip and these motions occur simultaneously? How consistent are these patterns across individuals?

One problem with using the CFLT as a clinical tool is the time constraint imposed by the photographic measurement procedure. Future research could also look at alternative, faster ways of measuring APT and HE during the CFLT such as visual inspection or with a digital inclinometer. To increase the generalizability, further research could also look at the CFLT in injured individuals, and/or in a non-runner group.

The sample used in this study consisted of both males and females. The current sample is too small to separate data based on sex, so future studies could also look at how using a male or female population would affect the outcomes. It is possible that males and females would at least have different normal values for hip and pelvic measurements during the CFLT.

In closing, it seems pertinent to discuss not only the findings and clinical implications of this study as it relates to the CFLT itself, but to also draw attention to the interpretation of clinical measurements in general. Musculoskeletal clinicians rely on clinical tests to gain valuable information on the health and functional status of their patients; however, clinicians seldom consider how these tests were developed, or what assumptions and limitations are associated with these tests. For example, what is normal? How reliable is a certain test? Do tests accurately reflect how the patient performs during real life activities? As effective clinical tests remain the cornerstone of diagnosis and treatment, it is important that clinicians develop a more complete understanding of testing procedures, including facets of validity, reliability, and measurement error. This will greatly enhance a clinicians' ability to perform and interpret those tests, which will in turn lead to more accurate diagnosis, and monitoring of treatment success.

Appendix A: Reliability Study Using a Sacral Wand to Represent the Pelvis

Although it is common both in clinical practice and in research settings to represent the pelvis as a straight line connecting the ASIS and PSIS, this can often be a problem as visualization of these landmarks can be difficult. Therefore, in addition to measuring the pelvis and hip in reference to markers attached to the ASIS and PSIS, an additional marker system consisting of two markers attached to a small wand protruding back away from the sacrum was also used. The wand was 20 cm in length and was attached either to compression shorts, or when possible, directly to the skin of each participant. The objective was to see how measurements using this sacral wand compared to the traditional ASIS-PSIS representation and to determine if this is a viable method with which to measure pelvic tilt and hip extension during the CFLT.

To distinguish measurements made using the sacral wand and those using the ASIS and PSIS landmarks, measurements made in reference to the sacral wand will be referred to as the sacral position or sacral tilt (ST). Measurements made in reference to the ASIS-PSIS will be referred to as pelvic tilt (PT). ST is defined as the angle formed by a line connecting the two markers on the sacral wand and a horizontal reference line. ST_{ROM} is defined as the difference between ST as measured in a relaxed standing position and that measured in the end position of the constrained forward lunge test (CFLT). The hip extension angle, represented by the angle formed between the ST angle and a straight line connecting the lateral femoral condyle and greater trochanter of the thigh, will be referred to as $HE_{T\text{-}S}$. $HE_{T\text{-}S\ ROM}$ is defined as the difference between the hip angle measured in a relaxed standing position and that measured at the end position of the CFLT

Intra-Rater Reliability

Within-day intra-rater reliability was calculated using ICC(3,1). Based on this model, which compares single measurements made by the same examiner ST_{ROM} and $HE_{T\text{-}S\ ROM}$ had ICC(3,1) values of 0.85 and 0.85 respectively (Table 16). For between-day intra-rater reliability, ICC(3,1) values for ST_{ROM} and $HE_{T\text{-}S\ ROM}$ were 0.82 and 0.84 respectively (Table 17). In addition to calculating reliability using single measurements, reliability was also calculated using ICC(3,k), which compares the mean of several measures taken by the same examiner. Between-day intra-rater reliability of photographic measures of ST_{ROM} and $HE_{T\text{-}S\ ROM}$ had ICC(3,k) values of 0.91 and 0.85 respectively (Table 17). Based on this data, it appears that the reliability of ST_{ROM} and $HE_{T\text{-}S\ ROM}$ are high, when using single measurements. This reliability increases slightly when using mean of several measurements.

In addition to ST_{ROM} and $HE_{T\text{-}S\ ROM}$, photographic measurements of the sacral tilt start position, sacral tilt end position, hip extension start position, and hip extension end position were also calculated. A summary of the within-day intra-rater reliability calculations associated with these variables can be found in Table 16. Between-day intra-rater reliability calculations can be found in Table 17.

Inter-Rater Reliability

Within-day inter-rater reliability was calculated using ICC(2,1). Based on this model, which compares single measurements made by several examiners on the same group of subjects, ST_{ROM} and $HE_{T\text{-}S\ ROM}$ had ICC(2,1) values of 0.98 and 0.93 respectively (Table 18). In addition to calculating reliability using single measurements, reliability was also calculated using ICC(2,k), which compares the mean of multiple measurements made by one examiner with the mean of multiple measurements made by other examiners. Within-day inter-rater reliability of photographic measures of ST_{ROM} and $HE_{T\text{-}S\ ROM}$ had ICC(2,k) values of 0.86 and 0.92 respectively (Table 18). It appears that when using individual measurements, reliability of ST_{ROM} and $HE_{T\text{-}S\ ROM}$ is high. Using the mean of several measures does not appear to consistently increase the reliability coefficient of these variables.

In addition to ST_{ROM} and $HE_{T\text{-}S\ ROM}$, photographic measurements of the sacral tilt start position, sacral tilt end position, hip extension start position, and hip extension end position were also calculated. A summary of the within-day inter-rater reliability

Table 16. ICC values calculated for hip and pelvic measurements using a sacral wand to represent the pelvis. Calculation are based on measurements taken from three separate constrained forward lunge tests performed on the same occasion (between trial intra-rater reliability).

	ICC(3,1)
ST Start	0.93
ST End	0.92
ST ROM	0.85
HE Start	0.94
HE End	0.92
HE ROM	0.85

Table 17. ICC values calculated for hip and pelvic measurements using a sacral wand to represent the pelvis. Calculations are based on measurements taken by a single examiner from constrained forward lunge tests performed on the two different days (between day intra-rater reliability).

	ICC(3,1)	ICC(3,k) 3 measurements
ST Start	0.85	0.92
ST End	0.81	0.86
ST ROM	0.82	0.91
HE Start	0.84	0.89
HE End	0.84	0.87
HE ROM	0.84	0.85

Table 18. ICC values calculated for hip and pelvic measurements using a sacral wand to represent the pelvis. Calculations are based on measurements taken by three different examiners from constrained forward lunge tests performed on the same occasion (within-day inter-rater reliability).

	ICC(2,1)	ICC(2,k) 3 measurements
ST Start	0.89	0.86
ST End	0.95	0.94
ST ROM	0.98	0.86
HE Start	0.94	0.89
HE End	0.95	0.94
HE ROM	0.93	0.92

calculations based on both individual measurements and the means of several measurements can be found in Table 18.

Standard Error of Measurement (SEM)

The SEMs corresponding to measurements made by a single rater using a sacral wand to represent the pelvis are provided in Table 19. With respect to measurements taken from 3 consecutive trials on the same day, the SEM for ST_{ROM} was 2.03 degrees, and for $HE_{ROM\ (T\text{-}S)}$ was 2.43 degrees. For measurements taken from 3 consecutive trials on two separate days, the SEMs for ST_{ROM} and $HE_{ROM\ (T\text{-}S)}$ are 2.56 degrees and 3.99 degrees respectively. When using the mean of three measurements from two separate days, the SEMs for ST_{ROM} and $HE_{ROM(T\text{-}S)}$ were 2.41 degrees and 4.54 degrees.

To aid in the interpretation of measurement results into clinical practice the smallest detectable difference (SDD) for each measurement (95% confidence interval corresponding to each measurement) is also provided in Table 19. The SDD shows that with respect to photographic measurements of ST_{ROM} and $HE_{ROM\ (T\text{-}S)}$ taken during the CFLT in healthy adult runners, when measurements are taken by the same rater on different days, only changes larger than 4.72 degrees for ST_{ROM} and 8.89 degrees for $HE_{ROM\ (T\text{-}S)}$ can be interpreted as real changes, assuming the mean of three measurements are used in calculating the associated pelvic and hip angles. If individual measurements are used, only changes in ST_{ROM} larger than 5.02 degrees, and changes in $HE_{ROM\ (T\text{-}S)}$ larger than 7.83 degrees can be interpreted as real changes.

The SEMs corresponding to measurements made by a three different raters within the same day are provided in Table 20. For measurements taken from 3 consecutive trials on the same day, the SEMs for ST_{ROM} and $HE_{ROM\ (T\text{-}S)}$ were 4.23 degrees and 4.59 degrees respectively. When using the mean of three measurements, the SEMs for PT_{ROM} and HE_{ROM} were 4.35 degrees and 4.67 degrees respectively.

Table 19. Standard error of measurement and smallest detectable difference values for photographic measurements of sacral tilt and hip extension range of motion taken by a single examiner when using a sacral wand to represent the pelvis.

	SEM (individual measurements)	**SDD**	**SEM (mean of 3 measurements)**	**SDD**
ST ROM				
Within-Day	2.03	3.99	-	-
Between-Day	2.56	5.02	2.41	4.72
HE ROM (T-S)				
Within-Day	2.43	4.76	-	-
Between-Day	3.99	7.83	4.54	8.89

Table 20. Standard error of measurement and smallest detectable difference values for photographic measurements of sacral tilt and hip extension range of motion taken by a three different examiners when using a sacral wand to represent the pelvis.

	SEM (individual measurements)	**SDD**	**SEM (mean of 3 measurements)**	**SDD**
ST ROM	4.23	8.28	4.35	8.53
HE ROM (T-S)	4.59	9.00	4.67	9.16

Table 21. Comparison of measurements using a sacral wand to represent the pelvis versus the traditional ASIS-PSIS landmarks. Calculations are based on measurements taken by a single examiner.

	APT_{ROM}	**ST_{ROM}**	**$HE_{ROM(T-P)}$**	**$HE_{ROM(T-S)}$**
Within-Day				
ICC(3,1)	0.64	0.85	0.89	0.90
SEM	2.70	2.03	2.75	2.43
Between-Day				
ICC(3,1)	0.75	0.82	0.76	0.80
SEM	2.85	2.56	4.63	3.99

Table 22. Comparison of measurements using a sacral wand to represent the pelvis versus the traditional ASIS-PSIS landmarks. Calculations are based on measurements taken by three different examiners.

	APT_{ROM}	ST_{ROM}	$HE_{ROM(T\text{-}P)}$	$HE_{ROM(T\text{-}S)}$
ICC(2,1)	0.86	0.98	0.90	0.93
SEM	3.34	4.23	4.94	4.59

Using a sacral wand versus the ASIS and PSIS

Based on the calculated intra-class correlation coefficients it appears photographic measurements utilizing a sacral wand to represent the pelvic segment is a reliable method to measure pelvic and hip ROM during the CFLT. A comparison of pelvic and hip ROM measurements utilizing a sacral wand versus the traditional ASIS and PSIS landmarks based on intra-rater reliability is presented in Table 21, and based on inter-rater reliability in Table 22. With respect to reliability and measurement error it appears there may be some advantage of using a sacral wand over the ASIS-PSIS method, as measurements using the sacral wand had slightly higher ICC values and slightly lower SEM values. The only exception to this was with the SEM for the range of motion of the pelvis as measured by multiple examiners (inter-rater reliability), in which SEM was 4.23 degrees for the sacral wand compared to 3.34 degrees for the ASIS-PSIS.

Although the ICC and SEM values when using the sacral wand are generally more favourable in comparison to the traditional the ASIS-PSIS representation of the pelvis, the use of a sacral wand to represent the pelvis is uncommon in both clinical practice and research. This makes it more difficult to compare measurements using a sacral wand to other research findings or clinical reference values. Furthermore, despite the generally lower SEM values seen with the sacral wand versus the ASIS-PSIS method, the overall SEM values, and therefore degree of change for both pelvic tilt ROM and hip extension ROM form one test session to another remains relatively high. Therefore, using a sacral wand still has the same problem of low sensitivity to changes in pelvic and hip motion as is seem with using the ASIS-PSIS method.

Appendix B: Participant Pre-Screening Participation Script

These questions are to be asked to the potential participant by the principal investigator when the potential participant initially contacts the principal investigator.

1. What is your year of your birth?
2. On average, how far do you run per week?
3. Either currently, or in the past 3 months, have you experience any pain or injury in your right or left leg, hip, pelvis, or back that has prevented you from running or caused you to take a day off from your normal running schedule?

Appendix C: Intake Questionnaire

Participant No:_______________________

DEMOGRAPHIC AND RUNNING HISTORY QUESTIONAIRRE

Project Title

Are measurements of hip extension and anterior pelvic tilt taken from static photographs during a Constrained Forward Lunge Test valid and reliable in healthy adult runners?

Please answer the following questions as accurately as possible.

1) Are you (please circle one):

   Female   Male

2) How Old Are You?

   Age _______________(years)

3) How Tall Are You?

   Height _______________(cm)

4) How Much Do You Weigh?

   Weight _______________(kg)

5) Either currently, or in the past 3 months, have you experience any pain or injury in your right or left leg, hip, pelvis, or back that has prevented you form running or caused you to take a day off from your normal running schedule?

   Yes   No

Appendix D: Data Tables

Valididy Calculations (Data used for Bland-Altman and ICC calculations for APT ROM and HE ROM)

Table F.1. Mean anterior pelvic tilt range of motion values obtained from photographic and Optotrak measurements

	Photograph Mean	**Optotrak Mean**	**Difference**
	-8.50	-5.59	-2.91
	-5.50	-4.66	-0.84
	-12.00	-11.38	-0.62
	-11.17	-8.24	-2.92
	-10.67	-9.51	-1.15
	-6.67	-5.72	-0.95
	-9.17	-7.93	-1.24
	-2.17	-0.01	-2.15
	-9.67	-8.21	-1.46
	-14.00	-11.19	-2.81
	-14.83	-14.00	-0.84
	-13.33	-12.35	-0.98
	-3.83	-4.30	0.47
Mean	**-9.35**	**-7.93**	**-1.42**
STD	**3.92**	**3.86**	**1.01**

Table F.2. Paired t-Test comparing the difference in means between photographic and Optotrak measurements of anterior pelvic tilt range of motion.

t-Test: Paired Two Sample for Means

	Photograph Mean	*Optotrak Mean*
Mean	-9.18974359	-7.930561446
Variance	40.15599715	14.8792448
Observations	13	13
Pearson Correlation	0.92955279	
Hypothesized Mean Difference	0	
df	12	
t Stat	-1.465907592	
P(T<=t) one-tail	0.084190738	
t Critical one-tail	1.782287548	
P(T<=t) two-tail	0.168381477	
t Critical two-tail	2.178812827	

Table F.3. ANOVA table analyzing the difference in means between photographic and Optotrak measurements of anterior pelvic tilt range of motion

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	356.9058547	12	29.742155	57.838571	1.035E-08	2.6866371
Within Subjects	13.02536198	1	13.025362	25.329985	0.0002928	4.7472253
Error	6.170723928	12	0.514227			
Total	376.1019406	25				

ICC(2,k) 0.94

Table F.4. Mean hip extension range of motion values obtained from photographic and Optotrak measurements

HE ROM	Photograph Mean	Optotrak Mean	Difference
	-8.33	-10.13	1.79
	-20.33	-20.97	0.63
	-19.50	-17.87	-1.63
	-9.00	-10.14	1.14
	-6.33	-6.54	0.21
	-19.00	-20.48	1.48
	-10.33	-10.11	-0.22
	-16.50	-17.30	0.80
	-5.33	-6.05	0.72
	-1.50	-3.33	1.83
	4.33	4.17	0.17
	-12.83	-12.60	-0.24
	-21.00	-19.61	-1.39
Mean	**-11.21**	**-11.61**	**0.41**
SD	**7.89**	**7.55**	**1.09**

Table F.5. Paired t-Test comparing the difference in means between photographic and Optotrak measurements of hip extension range of motion.

t-Test: Paired Two Sample for Means

	Photograph Mean1	*Optotrak Mean*
Mean	-11.20512821	-11.61287
Variance	62.26923077	56.950923
Observations	13	13
Pearson Correlation	0.991055619	
Hypothesized Mean Difference	0	
df	12	
t Stat	1.351096091	
P(T<=t) one-tail	0.100794503	
t Critical one-tail	1.782287548	
P(T<=t) two-tail	0.201589005	
t Critical two-tail	2.178812827	

Table F.6. ANOVA table analyzing the difference in means between photographic and Optotrak measurements of hip extension range of motion

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1423.538023	12	118.62817	200.39039	6.779E-12	2.6866371
Within Subjects	1.080645873	1	1.0806459	1.8254606	0.201589	4.7472253
Error	7.10382363	12	0.5919853			
Total	1431.722493	25				

ICC(2,k) 0.99

Intra-Rater Reliability Calculations for Anterior Pelvic Tilt (All data from Examiner 1)

Table F.7. Anterior pelvic tilt start positions for Day 1 and Day 2.

APT **Start Position**

Subject	D1 T1	D1 T2	D1 T3	D2 T1	D2 T2	D2 T3		Mean D1	Mean D2	SD1	SD2
1	-2.0	-3.5	-5.0	1.0	-1.0	-0.5		-3.50	-0.17	1.50	1.04
2	-6.5	-6.5	-7.0	-3.5	-5.0	-3.0		-6.67	-3.83	0.29	1.04
3	-6.5	-4.5	-7.0	-12.0	-12.0	-11.0		-6.00	-11.67	1.32	0.58
4	-5.0	-4.0	-4.0	-8.0	-10.0	-10.5		-4.33	-9.50	0.58	1.32
5	-10.0	-11.5	-11.0	-9.0	-10.0	-8.0		-10.83	-9.00	0.76	1.00
6	-10.0	-8.0	-11.5	-16.0	-17.0	-19.5		-9.83	-17.50	1.76	1.80
7	-2.0	-2.5	-3.0	-12.0	-12.5	-9.0		-2.50	-11.17	0.50	1.89
8	-2.5	-1.0	-5.0	-5.5	-5.0	-5.0		-2.83	-5.17	2.02	0.29
9	-1.5	-1.0	-0.5	-10.0	-12.5	-14.0		-1.00	-12.17	0.50	2.02
10	-6.0	-7.5	-6.5	-11.5	-8.0	-8.0		-6.67	-9.17	0.76	2.02
11	-2.0	-1.5	-2.0	-1.0	-1.5	-1.5		-1.83	-1.33	0.29	0.29
12	-1.5	-1.0	-0.5	-1.0	4.0	5.0		-1.00	2.67	0.50	3.21
13	-16.0	-16.5	-14.5	-18.0	-17.5	-19.0		-15.67	-18.17	1.04	0.76
							Means	**-5.59**	**-8.17**	**0.91**	**1.33**

Table F.8. Anova table analyzing anterior pelvic tilt start position measurements based on individual measurements from day 1 (within-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	686.6026	12	57.21688	52.0204	3.45E-14	2.18338
Within Subjects	2.935897	2	1.467949	1.334628	0.282101	3.402826
Error	26.39744	24	1.099893			
Total	715.9359	38				

ICC(3,1)	0.95
SEM	1.05

Table F.9. Anova table analyzing anterior pelvic tilt start position measurements based on individual measurements from day 1and day 2 (between-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1709.801	12	142.4834	16.56023	8.31E-15	1.917396
Within Subjects	133.0545	5	26.6109	3.092869	0.015029	2.36827
Error	516.2372	60	8.603953			
Total	2359.093	77				

ICC(3,1)	0.72
SEM	2.93

Table F.10. Anova table analyzing anterior pelvic tilt start position measurements based on the mean of measurements from day 1 and day 2 (between-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	569.9338	12	47.49448	3.996718	0.011692	2.686637
Within Subjects	43.16346	1	43.16346	3.632258	0.080901	4.747225
Error	142.6004	12	11.88337			
Total	755.6976	25				

ICC(3,k)	0.75
SEM	3.45

Table F.11. Anterior pelvic tilt end positions for Day 1 and Day 2.

APT **End Position**

Subject	**D1 T1**	**D1 T2**	**D1 T3**	**D2 T1**	**D2 T2**	**D2 T3**		**Mean D1**	**Mean D2**	**SD1**	**SD2**
1	-10.0	-14.0	-12.0	-8.0	-10.5	-11.0		-12.00	-9.83	2.01	2.00
2	-10.0	-13.0	-13.5	-7.5	-8.0	-6.5		-12.17	-7.33	2.95	1.89
3	-18.5	-17.5	-18.0	-24.0	-23.0	-26.5		-18.00	-24.50	3.75	0.50
4	-14.5	-18.0	-14.0	-21.5	-21.0	-21.0		-15.50	-21.17	3.40	2.18
5	-22.5	-18.5	-23.5	-21.0	-23.4	-23.0		-21.50	-22.47	1.93	2.65
6	-14.5	-18.0	-17.0	-23.5	-24.0	-25.0		-16.50	-24.17	4.38	1.80
7	-8.5	-12.5	-14.0	-22.0	-16.0	-15.0		-11.67	-17.67	4.45	2.84
8	-3.0	-5.0	-7.0	-3.5	-1.5	-0.5		-5.00	-1.83	2.35	2.00
9	-15.0	-6.5	-10.5	-23.0	-21.0	-19.0		-10.67	-21.00	6.39	4.25
10	-23.0	-18.0	-21.0	-26.0	-21.0	-22.0		-20.67	-23.00	2.64	2.52
11	-18.0	-13.0	-19.0	-23.5	-27.0	-19.0		-16.67	-23.17	4.82	3.21
12	-14.5	-13.5	-15.0	-8.5	-9.0	-10.5		-14.33	-9.33	2.86	0.76
13	-23.5	-17.0	-18.0	-20.5	-21.5	-18.5		-19.50	-20.17	2.44	3.50
							Means	**-14.94**	**-17.36**	**3.41**	**2.32**

Table F.12. Anova table analyzing anterior pelvic tilt end position measurements based on individual measurements from day 1 (within-day intra-rater)

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	768.5897	12	64.04915	10.09089	1.14E-06	2.18338
Within Subjects	12.66667	2	6.333333	0.997812	0.383471	3.402826
Error	152.3333	24	6.347222			
Total	933.5897	38				
ICC(3,1)	0.75					
SEM	2.52					

Table F.13. Anova table analyzing anterior pelvic tilt end position measurements based on individual measurements from day 1and day 2 (between-day intra-rater)

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	2362.677	12	196.8898	16.33572	1.12E-14	1.917396
Within Subjects	135.7538	5	27.15077	2.252669	0.060508	2.36827
Error	723.1628	60	12.05271			
Total	3221.594	77				
ICC(3,1)	0.72					
SEM	3.47					

Table F.14. Anova table analyzing anterior pelvic tilt end position measurements based on the mean of measurements from day 1 and day 2 (between-day intra-rater)

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	787.5591	12	65.62992	5.049947	0.0044149	2.686637
Columns	38.08274	1	38.08274	2.930307	0.112629006	4.747225
Error	155.9539	12	12.99616			
Total	981.5957	25				
ICC(3,k)	0.80					
SEM	3.61					

Table F.15. Anterior pelvic tilt range of motion measurements for Day 1 and Day 2

APT ROM

Subject	D1 T1	D1 T2	D1 T3	D2 T1	D2 T2	D2 T3		Mean D1	Mean D2	SD1	SD2
1	-8.0	-10.5	-7.0	-9.0	-9.5	-10.5		-8.50	-9.67	1.80	0.76
2	-3.5	-6.5	-6.5	-4.0	-3.0	-3.5		-5.50	-3.50	1.73	0.50
3	-12.0	-13.0	-11.0	-12.0	-11.0	-15.5		-12.00	-12.83	1.00	2.36
4	-9.5	-14.0	-10.0	-13.5	-11.0	-10.5		-11.17	-11.67	2.47	1.61
5	-12.5	-7.0	-12.5	-12.0	-13.4	-15.0		-10.67	-13.47	3.18	1.50
6	-4.5	-10.0	-5.5	-7.5	-7.0	-5.5		-6.67	-6.67	2.93	1.04
7	-6.5	-10.0	-11.0	-10.0	-3.5	-6.0		-9.17	-6.50	2.36	3.28
8	-0.5	-4.0	-2.0	2.0	3.5	4.5		-2.17	3.33	1.76	1.26
9	-13.5	-5.5	-10.0	-13.0	-8.5	-5.0		-9.67	-8.83	4.01	4.01
10	-17.0	-10.5	-14.5	-14.5	-13.0	-14.0		-14.00	-13.83	3.28	0.76
11	-16.0	-11.5	-17.0	-22.5	-25.5	-17.5		-14.83	-21.83	2.93	4.04
12	-13.0	-12.5	-14.5	-7.5	-13.0	-15.5		-13.33	-12.00	1.04	4.09
13	-7.5	-0.5	-3.5	-2.5	-4.0	0.5		-3.83	-2.00	3.51	2.29
							Means	**-9.35**	**-9.19**	**2.46**	**2.12**

Table F.16. Anova table analyzing anterior pelvic tilt ROM measurements based on individual measurements from day 1 (within-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	553.57692	12	46.13141	6.3335534	6.49E-05	2.183380082
Within Subjects	4.1923077	2	2.0961538	0.2877888	0.752472	3.402826105
Error	174.80769	24	7.2836538			
Total	732.57692	38				

ICC(3,1)	0.64
SEM	2.70

Table F.17. Anova table analyzing anterior pelvic tilt ROM measurements based on individual measurements from day 1and day 2 (between-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1840.12	12.00	153.34	18.89	0.00	1.92
Within Subjects	10.72	5.00	2.14	0.26	0.93	2.37
Error	487.18	60.00	8.12			
Total	2338.01	77.00				

ICC(3,1)	0.75
SEM	2.85

Table F.18. Anova table analyzing anterior pelvic tilt start position measurements based on the mean of measurements from day 1 and day 2 (between-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	613.37274	12	51.114395	11.56764202	8.246E-05	2.6866371
Within Subjects	0.1590171	1	0.1590171	0.035986982	0.8527134	4.7472253
Error	53.024872	12	4.4187393			
Total	666.55662	25				

ICC(3,k)	0. 91
SEM	2.10

Intra-Rater Reliability Calculations for Hip Extension (All data from Examiner 1)

Table F.19. Hip extension start position measurements for Day 1 and Day 2

HE **Start Position**

Subject	**D1 T1**	**D1 T2**	**D1 T3**	**D2 T1**	**D2 T2**	**D2 T3**		**Mean D1**	**Mean D2**	**SD1**	**SD2**
1	4.5	8.5	6.0	-3.0	-3.0	-3.0		6.33	-3.00	2.02	0.00
2	-1.0	-3.5	-3.5	-3.0	-3.0	-5.5		-2.67	-3.83	1.44	1.44
3	6.0	3.0	5.5	11.0	10.0	10.0		4.83	10.33	1.61	0.58
4	5.5	3.0	4.5	8.5	9.5	10.5		4.33	9.50	1.26	1.00
5	5.5	7.0	6.0	6.0	5.5	5.5		6.17	5.67	0.76	0.29
6	12.0	8.5	11.5	18.5	19.0	19.5		10.67	19.00	1.89	0.50
7	-1.5	0.0	0.0	13.0	12.0	10.0		-0.50	11.67	0.87	1.53
8	-2.0	1.0	0.5	1.0	1.5	-1.0		-0.17	0.50	1.61	1.32
9	-4.0	-5.0	-3.0	5.0	7.5	9.0		-4.00	7.17	1.00	2.02
10	8.5	9.0	9.0	16.0	14.0	11.0		8.83	13.67	0.29	2.52
11	-2.0	0.5	1.5	0.0	0.5	0.0		0.00	0.17	1.80	0.29
12	0.0	-2.0	-4.0	-4.5	-8.5	-10.0		-2.00	-7.67	2.00	2.84
13	12.0	12.0	8.5	16.5	16.0	15.5		10.83	16.00	2.02	0.50
							Means	**3.28**	**6.09**	**1.43**	**1.14**

Table F.20. Anova table analyzing hip extension start position measurements based on individual measurements from day 1 (within-day intra-rater)

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Subjects	950.3974	12	79.19979	31.46477	9.68E-12	2.18338
Within Subjects	0.089744	2	0.044872	0.017827	0.982344	3.402826
Error	60.41026	24	2.517094			
Total	1010.897	38				
ICC(3,1)	0.91					
SEM	1.59					

F.21. Anova table analyzing hip extension start position measurements based on individual measurements from day 1and day 2 (between-day intra-rater)

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Subjects	2711.513	12	225.9594	16.77224	6.28E-15	1.917396
Within Subjects	161.2083	5	32.24167	2.393196	0.047982	2.36827
Error	808.3333	60	13.47222			
Total	3681.054	77				
ICC(3,1)	0.72					
sem	3.67					

Table F.22. Anova table analyzing hip extension start position measurements based on the mean of measurements from day 1 and day 2 (between-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	903.8376	12	75.3198	3.862624	0.013385	2.686637
Within Subjects	51.24038	1	51.24038	2.62776	0.130973	4.747225
Error	233.9957	12	19.49964			
Total	1189.074	25				

ICC(3,k)	0.74
SEM	4.42

Table F.23. Hip extension end position measurements for Day 1 and Day 2

HE **End Position**

Subject	**D1 T1**	**D1 T2**	**D1 T3**	**D2 T1**	**D2 T2**	**D2 T3**		**Mean D1**	**Mean D2**	**SD1**	**SD2**
1	-2.5	0.5	-4.0	-9.0	-8.0	-7.0		-2.00	-8.00	2.29	1.00
2	-22.0	-24.0	-23.0	-27.0	-25.0	-27.5		-23.00	-26.50	1.00	1.32
3	-14.0	-16.0	-14.0	-6.0	-7.5	-5.0		-14.67	-6.17	1.15	1.26
4	-8.0	-3.0	-3.0	-2.5	-1.0	-1.0		-4.67	-1.50	2.89	0.87
5	-3.0	-1.5	4.0	14.5	11.5	12.0		-0.17	12.67	3.69	1.61
6	-9.5	-7.5	-8.0	8.5	8.0	10.0		-8.33	8.83	1.04	1.04
7	-14.0	-10.0	-8.5	10.0	6.0	6.0		-10.83	7.33	2.84	2.31
8	-18.0	-17.5	-14.5	-19.5	-19.5	-21.5		-16.67	-20.17	1.89	1.15
9	-7.0	-9.0	-12.0	5.0	2.0	0.0		-9.33	2.33	2.52	2.52
10	5.5	11.0	5.5	-2.0	-7.0	-7.5		7.33	-5.50	3.18	3.04
11	7.0	0.5	5.5	10.0	10.0	10.0		4.33	10.00	3.40	0.00
12	-15.0	-14.0	-15.5	-22.0	-21.0	-21.0		-14.83	-21.33	0.76	0.58
13	-9.0	-10.5	-11	-3.0	-2.5	-5.0		-10.17	-3.50	1.04	1.32
							Means	**-7.92**	**-3.96**	**2.13**	**1.39**

Table F.24. Anova table analyzing hip extension end position measurements based on individual measurements from day 1 (within-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	2704.436	12	225.3697	38.99187	8.94E-13	2.18338
Within Subjects	5.115385	2	2.557692	0.442514	0.647556	3.402826
Error	138.7179	24	5.779915			
Total	2848.269	38				

ICC(3,1)	0.93
SEM	2.40

Table F.25. Anova table analyzing hip extension end position measurements based on individual measurements from day 1and day 2 (between-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	6733.205	12	561.1004	17.42386	2.7E-15	1.917396
Within Subjects	324.6538	5	64.93077	2.016296	0.08915	2.36827
Error	1932.179	60	32.20299			
Total	8990.038	77				

ICC(3,1)	0.73
SEM	5.68

Table F.26. Anova table analyzing hip extension end position measurements based on the mean of measurements from day 1 and day 2 (between-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	2244.402	12	187.0335	3.880064	0.01315	2.686637
Within Subjects	104	1	104	2.157511	0.167596	4.747225
Error	578.4444	12	48.2037			
Total	2926.846	25				

ICC(3,k)	0.74
SEM	6.94

Table F.27. Hip extension range of motion measurements for Day 1 and Day 2

.

HE **ROM**

Subject	**D1 T1**	**D1 T2**	**D1 T3**	**D2 T1**	**D2 T2**	**D2 T3**		**Mean D1**	**Mean D2**	**SD1**	**SD2**
1	-7.0	-8.0	-10.0	-6.0	-5.0	-4.0		-8.33	-5.00	1.53	1.00
2	-21.0	-20.5	-19.5	-24.0	-22.0	-22.0		-20.33	-22.67	0.76	1.15
3	-20.0	-19.0	-19.5	-17.0	-17.5	-15.0		-19.50	-16.50	0.50	1.32
4	-13.5	-6.0	-7.5	-11.0	-10.5	-11.5		-9.00	-11.00	3.97	0.50
5	-8.5	-8.5	-2.0	8.5	6.0	6.5		-6.33	7.00	3.75	1.32
6	-21.5	-16.0	-19.5	-10.0	-11.0	-9.5		-19.00	-10.17	2.78	0.76
7	-12.5	-10.0	-8.5	-3.0	-6.0	-4.0		-10.33	-4.33	2.02	1.53
8	-16.0	-18.5	-15.0	-20.5	-21.0	-20.5		-16.50	-20.67	1.80	0.29
9	-3.0	-4.0	-9.0	0.0	-5.5	-9.0		-5.33	-4.83	3.21	4.54
10	-3.0	2.0	-3.5	-18.0	-21.0	-18.5		-1.50	-19.17	3.04	1.61
11	9.0	0.0	4.0	10.0	9.5	10.0		4.33	9.83	4.51	0.29
12	-15.0	-12.0	-11.5	-17.5	-12.5	-11.0		-12.83	-13.67	1.89	3.40
13	-21.0	-22.5	-19.5	-19.5	-18.5	-20.5		-21.00	-19.50	1.50	1.00
							Means	**-11.21**	**-10.05**	**2.41**	**1.44**

Table F.28. Anova table analyzing hip extension ROM measurements based on individual measurements from day 1 (within-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	2241.69	12.00	186.81	24.73	0.00	2.18
Within Subjects	6.36	2.00	3.18	0.42	0.66	3.40
Error	181.31	24.00	7.55			
Total	2429.36	38.00				

ICC(3,1)	0.89
SEM	2.75

Table F.29. Anova table analyzing hip extension ROM measurements based on individual measurements from day 1and day 2 (between-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	5088.5321	12	424.04434	19.761191	1.568E-16	1.9173959
Within Subjects	36.785256	5	7.3570513	0.3428512	0.8848466	2.3682702
Error	1287.5064	60	21.45844			
Total	6412.8237	77				

ICC(3,1)	0.76
SEM	4.63

Table F.30. Anova table analyzing hip extension ROM measurements based on the mean of measurements from day 1 and day 2 (between-day intra-rater)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1696.17735	12	141.3481125	4.9933071	0.0046355	2.6866371
Within Subjects	9.240384615	1	9.240384615	0.3264287	0.5783137	4.7472253
Error	339.6901709	12	28.30751425			
Total	2045.107906	25				

ICC(3,k)	0.80
SEM	5.32

Inter-Rater Reliability Calculations for APT

Table F.31. Anterior pelvic tilt start position measurements for examiners 1,2, and 3. All measurements were performed on the same day

APT **Start Position**

Subject	**E1 T1**	**E1 T2**	**E1 T3**	**E2 T1**	**E2 T2**	**E2 T3**	**E3 T1**	**E3 T2**	**E3 T3**	**Mean E1**	**Mean E2**	**Mean E3**
1	-6.5	-6.5	-7.0	-5.0	-7.0	-6.5	-8.0	-5.0	-10.0	-6.67	-6.17	-7.67
2	-10.0	-11.5	-11.0	-6.0	-3.5	-9.0	-11.0	-13.0	-12.5	-10.83	-6.17	-12.17
3	-10.0	-8.0	-11.5	-12.0	-12.0	-11.0	-17.5	-15.0	-14.0	-9.83	-11.67	-15.50
4	-2.0	-2.5	-3.0	-10.0	-9.0	-8.0	-16.0	-15.0	-17.0	-2.50	-9.00	-16.00
5	-1.5	-1.0	-0.5	-7.5	-8.0	-7.75	-12.0	-16.5	-15.0	-1.00	-7.75	-14.50
6	-6.0	-7.5	-6.5	-10.5	-8.5	-8.0	-10.0	-9.0	-11.0	-6.67	-9.00	-10.00
7	-2.0	-1.5	-2.0	-1.0	-2.5	-1.5	-6.5	-6.0	-6.0	-1.83	-1.67	-6.17
8	-1.5	-1.0	-0.5	-3.0	-3.0	0.5	-11.0	-6.0	-5.0	-1.00	-1.83	-7.33
9	-16.0	-16.5	-14.5	-17.0	-16.0	-15	-12.0	-13.0	-12.5	-15.67	-16.00	-12.50

Table F.32. Anova table analyzing anterior pelvic tilt start position based on individual measurements from examiners 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1013.386	8	126.6732	15.01072	3.96E-12	2.086758
Within Subjects	374.6914	8	46.83642	5.550095	2.44E-05	2.086758
Error	540.0864	64	8.43885			
Total	1928.164	80				

ICC(2,1)	0.76
SEM	2.91

Table F.33. Anova table analyzing anterior pelvic tilt start position measurements based on the mean of three measurements from examiner 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	337.7953	8	42.22441	4.613937	0.004533	2.591096
Within Subjects	123.6271	2	61.81353	6.754476	0.00747	3.633723
Error	146.4239	16	9.151492			
Total	607.8462	26				

ICC(2,k)	0.69
SEM	3.03

Table F.34. Anterior pelvic tilt end position measurements for examiners 1,2, and 3. All measurements were performed on the same day

APT End Position

Subject	E1 T1	E1 T2	E1 T3	E2 T1	E2 T2	E2 T3	E3 T1	E3 T2	E3 T3	Mean E1	Mean E2	Mean E3
1	-10.0	-13.0	-13.5	-8.0	-7.5	-10.0	-14.0	-12.5	-11.5	-12.17	-8.50	-12.67
2	-22.5	-18.5	-23.5	-22.0	-25.0	-20.0	-22.0	-24.5	-20.5	-21.50	-22.33	-22.33
3	-14.5	-18.0	-17.0	-19.0	-18.0	-15.5	-28.0	-23.0	-24.0	-16.50	-17.50	-25.00
4	-8.5	-12.5	-14.0	-12.0	-10.0	-13.0	-17.0	-19.5	-18.0	-11.67	-11.67	-18.17
5	-15.0	-6.5	-10.5	-15.0	-16.0	-15.5	-29.0	-28.25	-27.5	-10.67	-15.50	-28.25
6	-23.0	-18.0	-21.0	-22.0	-16.5	-20.0	-30.0	-30.5	-31.5	-20.67	-19.50	-30.67
7	-18.0	-13.0	-19.0	-16.0	-19.0	-17.0	-21.0	-21.0	-23.0	-16.67	-17.33	-21.67
8	-14.5	-13.5	-15.0	-19.0	-16.0	-17.0	-19.0	-20.0	-19.5	-14.33	-17.33	-19.50
9	-23.5	-17.0	-18.0	-21.0	-19.0	-20.0	-15.0	-15.5	-14.0	-19.50	-20.00	-14.83

Table F.35. Anova table analyzing anterior pelvic tilt end position based on individual measurements from examiners 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1050.821	8	131.3526	10.40079	3.37E-09	2.086758
Within Subjects	521.4599	8	65.18248	5.161293	5.49E-05	2.086758
Error	808.2623	64	12.6291			
Total	2380.543	80				

ICC(2,1)	0.68
SEM	3.55

Table F.36. Anova table analyzing anterior pelvic tilt end position measurements based on the mean of three measurements from examiner 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	350.2737	8	43.78421	3.410919	0.017562	2.591096
Within Subjects	161.5931	2	80.79655	6.29429	0.009625	3.633723
Error	205.3837	16	12.83648			
Total	717.2505	26				

SEM	3.58
ICC(2,k)	0.60

Table F.37. Anterior pelvic tilt ROM measurements for examiners 1,2, and 3. All measurements were performed on the same day

APT ROM

Subject	E1 T1	E1 T2	E1 T3	E2 T1	E2 T2	E2 T3	E3 T1	E3 T2	E3 T3	Mean E1	Mean E2	Mean E3
1	-3.5	-6.5	-6.5	-3.0	-0.5	-3.5	-6.0	-7.5	-1.5	-5.50	-2.33	-5.00
2	-12.5	-7.0	-12.5	-16.0	-21.5	-11.0	-11.0	-11.5	-8.0	-10.67	-16.17	-10.17
3	-4.5	-10.0	-5.5	-7.0	-6.0	-4.5	-10.5	-8.0	-10.0	-6.67	-5.83	-9.50
4	-6.5	-10.0	-11.0	-2.0	-1.0	-5.0	-1.0	-4.5	-1.0	-9.17	-2.67	-2.17
5	-13.5	-5.5	-10.0	-7.5	-8.0	-7.75	-17.0	-11.75	-12.5	-9.67	-7.75	-13.75
6	-17.0	-10.5	-14.5	-11.5	-8.0	-12.0	-20.0	-21.5	-20.5	-14.00	-10.50	-20.67
7	-16.0	-11.5	-17.0	-15.0	-16.5	-15.5	-14.5	-15.0	-17.0	-14.83	-15.67	-15.50
8	-13.0	-12.5	-14.5	-16.0	-13.0	-17.5	-8.0	-14.0	-14.5	-13.33	-15.50	-12.17
9	-7.5	-0.5	-3.5	-4.0	-3.0	-5.0	-3.0	-2.5.0	-1.5	-3.83	-4.00	-2.33

Table F.38. Anova table analyzing anterior pelvic tilt ROM based on individual measurements from examiners 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1652.802	8	206.6003	18.53891	5.01E-14	2.086758
Within Subjects	58.20525	8	7.275656	0.652868	0.730374	2.086758
Error	713.2253	64	11.14415			
Total	2424.233	80				

ICC(2,1)	0.86
SEM	3.34

Table F.39. Anova table analyzing anterior pelvic tilt ROM measurements based on the mean of three measurements from examiner 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	550.9342	8	68.86677	7.926347	0.000248	2.591096
Within Subjects	6.769033	2	3.384516	0.389547	0.683615	3.633723
Error	139.0134	16	8.688336			
Total	696.7166	26				

ICC(2,k)	0.88
SEM	2.95

Inter-Rater Reliability Calculations for Hip Extension

Table F.40. Hip extension start position measurements for examiners 1,2, and 3. All measurements were performed on the same day

HE Start Position

											Means	
Subject	**E1 T1**	**E1 T2**	**E1 T3**	**E2 T1**	**E2 T2**	**E2 T3**	**E3 T1**	**E3 T2**	**E3 T3**	**E1**	**E2**	**E3**
1	-1.0	-3.5	-3.5	3.0	2.0	4.0	-1.0	-1.5	-1	-2.67	3.00	-1.17
2	5.5	7.0	6.0	5.0	3.0	7.0	4.5	7.0	5.0	6.17	5.00	5.50
3	12.0	8.5	11.5	13	13.0	11.0	16.5	21	20.0	10.67	12.33	19.17
4	-1.5	0.0	0.0	9.5	10.0	10.0	14.5	14	15.5	-0.50	9.83	14.67
5	-4.0	-5.0	-3.0	9.0	8.0	8.5	8.0	10	12.0	-4.00	8.50	10.00
6	8.5	9.0	9.0	15.0	17.5	14.0	9.0	9.0	9.0	8.83	15.50	9.00
7	-2.0	0.5	1.5	3.0	2.0	1.0	8.5	6.0	6.0	0.00	2.00	6.83
8	0.0	-2.0	-4.0	2.0	3.0	-2.5	-0.5	0.0	1.5	-2.00	0.83	0.33
9	12.0	12.0	8.5	19.0	17.0	17.0	6.5	5.5	8.0	10.83	17.67	6.67

Table F.41. Anova table analyzing hip extension start position based on individual measurements from examiners 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1943.833	8	242.9792	17.45414	1.81E-13	2.086758
Within Subjects	472.7778	8	59.09722	4.245183	0.000394	2.086758
Error	890.9444	64	13.92101			
Total	3307.556	80				

ICC(2,1)	0.80
SEM	3.73

Table F.42. Anova table analyzing hip extension start position based on the mean of three measurements from examiner 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	647.9444	8	80.99306	4.937184	0.003254	2.591096
Within Subjects	154.0988	2	77.04938	4.696785	0.024841	3.633723
Error	262.4753	16	16.40471			
Total	1064.519	26				

ICC(2,k)	0.74
SEM	4.05

HE End Position

Table F.43. Hip extension end position measurements for examiners 1,2, and 3. All measurements were performed on the same day

HE	**Start Position**										
										Means	
Subject	**E1 T1**	**E1 T2**	**E1 T3**	**E2 T1**	**E2 T2**	**E2 T3**	**E3 T1**	**E3 T2**	**E3 T3**	**E1**	**E2**	**E3**
1	-22.0	-24.0	-23.0	-23.0	-23.0	-21.5	-25	-25.0	-21.0	-23.00	-22.50	-23.67
2	-3.0	-1.5	4.0	7.0	12.0	8.0	5.0	8.0	-1.5	-0.17	9.00	3.83
3	-9.5	-7.5	-8.0	-4.0	-3.0	-7.0	4.4	4.0	4.0	-8.33	-4.67	4.13
4	-14.0	-10.0	-8.5	-6.0	-2.5	4.5	7.0	8.0	9.0	-10.83	-1.33	8.00
5	-7.0	-9.0	-12.0	-9.0	-5.0	-7.0	10.0	8.5	7.0	-9.33	-7.00	8.50
6	5.5	11.0	5.5	-4.0	-8.0	-6.0	-9.0	-5.0	-8.5	7.33	-6.00	-7.50
7	7.0	0.5	5.5	4.0	5.5	4.0	12.0	14.5	15.5	4.33	4.50	14.00
8	-15.0	-14.0	-15.5	-11.0	-10.0	-13.0	-12.0	-11.0	-11.0	-14.83	-11.33	-11.33
9	-9.0	-10.5	-11.0	4.0	0.0	3.0	-11.5	-10.0	-9.0	-10.17	2.33	-10.17

Table F.44. Anova table analyzing hip extension end position based on individual measurements from examiners 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	5891.18	8	736.3975	20.93653	3.48E-15	2.086758
Within Subjects	443.8467	8	55.48083	1.577377	0.149311	2.086758
Error	2251.062	64	35.17285			
Total	8586.089	80				

ICC(2,1)	0.86
SEM	5.93

Table F.45. Anova table analyzing hip extension end position measurements based on the mean of three measurements from examiner 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1963.727	8	245.4658	6.011326	0.001176	2.591096
Within Subjects	143.8696	2	71.93481	1.761645	0.203487	3.633723
Error	653.3422	16	40.83389			
Total	2760.939	26				

ICC(2,k)	0.82
SEM	6.39

<u>HE ROM</u>

Table F.46. Hip extension ROM measurements for examiners 1,2, and 3. All measurements were performed on the same day

HE	**ROM**									**Means**	
Subject	**E1 T1**	**E1 T2**	**E1 T3**	**E2 T1**	**E2 T2**	**E2 T3**	**E3 T1**	**E3 T2**	**E3 T3**	**E1**	**E2**	**E3**
1	-21.0	-20.5	-19.5	-26.0	-25.0	-25.5	-24.0	-23.5	-20.0	-20.33	-25.50	-22.50
2	-8.5	-8.5	-2.0	2.0	9.0	1.0	0.5	1.0	-6.5	-6.33	4.00	-1.67
3	-21.5	-16.0	-19.5	-17.0	-16.0	-18.0	-12.0	-17.0	-16.0	-19.00	-17.00	-15.03
4	-12.5	-10.0	-8.5	-15.5	-12.5	-5.5	-7.5	-6.0	-6.5	-10.33	-11.17	-6.67
5	-3.0	-4.0	-9.0	-18.0	-13.0	-15.5	2.0	-1.5	-5.0	-5.33	-15.50	-1.50
6	-3.0	2.0	-3.5	-19.0	-25.5	-20.0	-18.0	-14.0	-17.5	-1.50	-21.50	-16.50
7	9.0	0.0	4.0	1.0	3.5	3.0	3.5	8.5	9.5	4.33	2.50	7.17
8	-15.0	-12.0	-11.5	-13.0	-13.0	-10.5	-11.5	-11.0	-12.5	-12.83	-12.17	-11.67
9	-21.0	-22.5	-19.5	-15.0	-17.0	-14.0	-18.0	-15.5	-17.0	-21.00	-15.33	-16.83

Table F.47. Anova table analyzing hip extension ROM based on individual measurements from examiners 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	5216.413	8	652.0517	26.67871	1.27E-17	2.086758
Within Subjects	151.0689	8	18.88361	0.772623	0.628033	2.086758
Error	1564.218	64	24.4409			
Total	6931.7	80				

ICC(2,1)	0.90
SEM	4.94

Table F.48. Anova table analyzing hip extension ROM measurements based on the mean of three measurements from examiner 1,2, and 3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Subjects	1738.804	8	217.3506	8.803848	0.000133	2.591096
Within Subjects	41.6721	2	20.83605	0.84397	0.448272	3.633723
Error	395.0101	16	24.68813			
Total	2175.487	26				

ICC(2,k)	0.89
SEM	4.97

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