

**THE EFFECT OF FEMOROACETABULAR DEFORMITY ON LOWER-LIMB JOINT BIOMECHANICS
DURING DAILY FUNCTIONAL TASKS**

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Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements for the degree of
Master's of Science in Human Kinetics

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Acknowledgements

I would like to thank my fellow students and friends Daniel Varin, Giulia Mantovani, K.C. Geoff Ng, Teresa Flaxman, and Matthew Kennedy for always offering their help; it was much needed and always appreciated. A major thank you goes out to my supervisor, Dr. Mario Lamontagne, for his patience and invaluable help and knowledge throughout the process.

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Abstract

Femoroacetabular impingement (FAI) is a hip joint deformity that causes joint pain, decreases joint range of motion and results in abnormal kinematic and kinetic characteristics. It is not known whether these biomechanical variations are caused by the actual mechanical impingement aspect of hip deformity or neuromuscular adaptations and soft tissue damage associated with pain. The purpose of this study was to investigate the effects of femoroacetabular cam deformity (FAD) during daily functional tasks. This was accomplished by measuring and comparing the hip joint biomechanics of symptomatic FAI (sFAI), asymptomatic FAD, and control (CON) subjects. Fifty one subjects volunteered to the study (n = 51; CON = 17, FAD = 18, sFAI = 16) and they performed 6 simulated activities of daily living: stair ascent and descent, sit-to-stand and stand-to-sit, dynamic range of motion, maximum depth squats and level walking tasks while motion ground reaction force and muscle activity were recorded. However, only the squat and level walking tasks were analyzed for this thesis. For each task, three-dimensional kinematics and kinetics were recorded and analyzed. Qualitative questionnaires (HOOS and WOMAC) and physical exams were also part of the testing protocol, and maximum voluntary isometric contractions (MVIC) were collected as part of a separate EMG protocol. The EMG results were not analyzed but the MVIC results were and the moments of force were determined. The sFAI group had significantly reduced scores for all HOOS and WOMAC metrics compared to FAD and CON. The sFAI group had significantly reduced external rotation, internal rotation, and a trend indicating reduced hip flexion compared to FAD and CON groups. The FAD group had a trend indicating reduced internal rotation compared to CON. There were no differences in the moments of force between groups for the MVICs. No

statistically significant differences were observed between groups for the squat trials, however, the sFAI group showed biomechanical variations. Both the CON and FAD groups were able to squat deeper, had greater pelvic range of motion and a larger maximum hip and knee flexion angle compared to sFAI. Similarly, the walking tasks did not elucidate any between group differences in biomechanical characteristics. Yet, there was a noticeable trend of decreased peak hip abduction angle in the sFAI group compared to CON. This result may be indicative of a gait adaptation based on the pain that sFAI subjects endure over a long period of time.

Interestingly, the FAD group did not have obvious gait patterns similar to either the CON or sFAI, making it unclear if the asymptomatic cam deformity has any gait adaptation effects. Since no differences were observed between FAD and CON in squatting and walking, the actual bone deformity may not be the cause of restricted motion during daily activities as previously thought. Internal rotation physical examination appears to indicate potential restrictions in the FAD compared to CON, and may be the best parameter to assess differences between groups and predict the presence of cam deformity. It is suggested that the presence of pain, caused by soft tissue damage over time, may be confounding factors leading to the biomechanical and neuromuscular discrepancies observed in sFAI, and should be the next avenue of study.

Introduction

Femoroacetabular Impingement (FAI) is an anatomical deformity located at the hip joint that causes pain and restricted motion in those who suffer from the disorder (Crawford and Villar 2005; Wisniewski and Grogg 2006). Evidence suggests the mechanism behind its pathology leads to labral degeneration and articular cartilage damage and causes further detrimental changes in the surrounding tissue due to the constant abrasion of the femoral and acetabular articular surfaces (Ganz, Parvizi et al. 2003; Beck, Kalhor et al. 2005; Crawford and Villar 2005). It has already been shown that FAI alters hip joint biomechanics, which, in turn, can limit one's capability of accomplishing activities of daily living and participating in sports (Kennedy, Lamontagne et al. 2009; Lamontagne, Kennedy et al. 2009; Hunt, Gunether et al. 2013). FAI is believed to be one possible cause of early onset osteoarthritis (OA) (Harris 1986; Ito, Minka et al. 2001; Ganz, Parvizi et al. 2003; Lavigne, Parvizi et al. 2004; Leunig and Ganz 2005). Therefore, the development of an effective screening program for FAI could identify potential patients early enough, before substantial degenerative changes in the cartilage can occur. If this is successful it may also prevent future need for total hip arthroplasty, consequently improving quality of life and reducing an important cost and burden to the health care system.

Purpose

The purpose of this study was to investigate lower-limb joint biomechanics in participants diagnosed with symptomatic FAI, asymptomatic femoroacetabular cam deformity

(FAD) and an age and BMI matched healthy control (CON) group during simulated daily activities. If both FAD and sFAI share the similar hip deformity, yet sFAI suffer pain, do differences in biomechanical variables exist between the two groups? If so, what are these differences and how do they compare to healthy controls?

In order to test for biomechanical variations between groups, maximal depth squats and level walking tasks were analyzed to assess participant's lower limb kinematics and kinetics. Commonly used physical examinations most often used by hip specialists were performed to test for the efficacy of the examinations ability to accurately diagnose FAI compared to controls and test for deficiencies in FAD.

Relevancy

Several studies have investigated the biomechanical effects of FAI during daily motion tasks, but no study has investigated FAD. The asymptomatic condition is fairly common in the general population, at a prevalence of 26% (Hack, Diprimio et al. 2009; Hack, Di Primio et al. 2010). It is important to determine if FAD has a corresponding effect on movement, and understand the relationship between asymptomatic FAD and symptomatic FAI. If certain movements in FAD participants can be isolated and used a predictor for early FAI, this may lead to new methods that can be used as early diagnosis to prevent future OA. Given the current health care burden of OA, forming a more comprehensive idea of the etiology of FAI and its relation to asymptomatic FAD is necessary to help understand both conditions and potentially decrease the financial impact FAI and OA place on the health care system. Most studies on FAI

were done in North American and European populations, so the generalization to the entire global population is unclear, as it is speculated that western lifestyle may lead to OA (Yamamura, Miki et al. 2007). However, FAI is a common condition in North America and European populations, and therefore a relevant area of study that encompasses a large portion of the global population.

Literature Review

Femoroacetabular Impingement

Femoroacetabular impingement is a hip joint deformity that affects the articulating surfaces of the femoral head and acetabular rims, and directly results in abnormal contact between the two surfaces (Ganz, Parvizi et al. 2003). Typically the contact occurs at the anterosuperior aspect of the femoral head (Sutter, Dietrich et al. 2012). The deformity can manifest as either a widening of the femoral neck or a decreased offset at the anterolateral femoral head-neck junction, which results in repeated contact between the femoral head and acetabular rim (Crawford and Villar 2005; Wisniewski and Grogg 2006; Leunig, Beaulé et al. 2009). The resulting anterior hip pain, labral tears and constant groin pain, as well as damage to the acetabular articular cartilage, are often symptoms common to people with FAI (Ito, Leunig et al. 2004; Philippon, Maxwell et al. 2007; Speirs, Beaulé et al. 2013). The condition is chronic and worsens over time with continued wear. Numerous studies have discussed FAI's causal connection to arthritis and it has often been defined as a major cause of pre-arthritis for the hip (Crawford and Villar 2005; Leunig and Ganz 2005; Leunig, Beaulé et al. 2009).

Two distinct types of FAI have been identified: Cam FAI and pincer FAI. Cam FAI is more common in athletic, young males, and pincer FAI is usually found in athletic, middle aged females (Reynolds, Lucas et al. 1999; Notzli, Wyss et al. 2002; Siebenrock, Schoeniger et al. 2003; Beaulé, Zaragoza et al. 2005). Cam FAI is believed to have a 10-15% prevalence rate in the male population and a 4% prevalence rate in the female population (Leunig and Ganz 2005; Jung, Restrepo et al. 2011).

The cause of cam FAI is due to an aspherical portion of the femoral head contacting the acetabular rim, leading to persistent wear of the femoral head against the acetabular rim resulting in damage to the articular cartilage. This type of contact interference occurs during hip flexion and internal rotation (Ito, Minka et al. 2001; Crawford and Villar 2005). In fact, both of these movements are used by physicians as a simple physical exam to test for cam FAI (Martin, Kelly et al. 2010; Nussbaumer, Leunig et al. 2010). In severe cases painful symptoms of cam FAI have been known to occur within the normal range of motion (Ito, Minka et al. 2001). Normally, impingement arises at the limits of hip motion, especially at high speeds or forces. As a result, it is often seen mostly in younger athletic males who utilize a full range of motion. Flexible athletes such as hockey goalies are particularly prone to cam FAI (Bizzini, Notzli et al. 2007). Cam FAI usually results in more serious damage than pincer type (Ganz, Parvizi et al. 2003), and long-term cam impingement can lead to labral and chondral lesions in the anterosuperior region of the acetabulum and shearing of the labrum and adjacent acetabular articular cartilage (Leunig, Casillas et al. 2000; Ganz, Parvizi et al. 2003; Crawford and Villar 2005).

In pincer type FAI, the femoral head neck contour is usually normal but prominence of the anterior wall of the acetabulum leads to abnormal contact between the labrum and femoral neck. The pathology in this situation arises when the labrum has repeated contact and compression between the femoral neck and the underlying acetabular bone. Since this usually is isolated to one specific area of the acetabulum, often the anterior aspect, there is a repeated microtrauma along a narrow band of the acetabular rim. Bone growth at the base of the labrum subsequently ossifies (Beck, Kalhor et al. 2005). Degeneration of the labrum frequently occurs as a consequence of persistent wear of the joint (Reynolds, Lucas et al. 1999; Siebenrock,

Schoeniger et al. 2003). The acetabular deformity associated with pincer FAI may be localized (i.e. acetabular retroversion in which just the anterior aspect of the acetabulum is extended and causing contact) or the deformity may be generalized as coxa profunda, in which the entire acetabular socket is too deep.

Pincer and cam FAI are not necessarily mutually exclusive pathologies – a combination of cam and pincer FAI is more common than either instance occurring independently (Beck, Kalhor et al. 2005).

In order to minimize the number of independent variables, only cam FAI was chosen to be studied. Since they have unique pathomechanics, it is appropriate to rule out pincer FAI for the study by means of radiograph and MRI. More cam FAI volunteers are available for recruitment and since cam FAI often results in more serious damage, it is more meaningful to study cam FAI.

Diagnosis and Physical Exams

FAI patients often feel pain localized to the groin area, or referred pain to the buttock area and down the iliotibial band (Philippon, Maxwell et al. 2007). The pain is constant, and most often felt during activity, but during long periods of sitting, initiation of walking or sustained hip flexion the pain may take the form of occasional sharp pains (Ganz, Parvizi et al. 2003; Leunig and Ganz 2005; Philippon and Schenker 2006). For a typical physical examination, the gait pattern will be relatively normal with some patients exhibiting a short stance phase (antalgic gait). Both cam and pincer FAI patients will have a positive impingement test with

flexion, internal rotation and adduction (Martin, Kelly et al. 2010; Nussbaumer, Leunig et al. 2010). In cam type FAI, patients will exhibit restricted internal rotation as overall restricted hip flexion.

There are various techniques to quantify the level and type of FAI, one of which is the α -angle (Notzli, Wyss et al. 2002). Notzli established a method to measure the asphericity of the femoral head-neck junction in order to quantify cam impingement. An α -angle of higher than 50.5° indicates cam type FAI while an α -angle less than 50.5° shows a normal curvature of the femoral head. It was hypothesized that larger the alpha angles will mean there is a lower free range of motion before impingement occurs. However, this idea was based off the observed limited internal rotation and the concept of the physical impingement acting as a restricting mechanism in the high alpha angle group, but no evidence of this has occurred for other motions. The concept is still a relevant idea but should not be extrapolated for all motions, given the lack of evidence in its favour.

Physicians have a wide range of diagnostic techniques available for detecting FAI. Modern techniques using CT scans and MRI to identify axial and radial sequences can reveal deformity in the hip joint (Notzli, Wyss et al. 2002; Hack, Diprimio et al. 2009; Rakhra, Sheikh et al. 2009; Sutter, Dietrich et al. 2012; Sutter, Dietrich et al. 2012). Another common method is to use the AP radiograph to identify α -angles greater than 50° on the Dunn View (Meyer, Beck et al. 2006; Allen, Beaulé et al. 2009). However, physicians often rely on simple physical exams such as the impingement test and internal rotation to help diagnose hip disorders. Common tests physicians use includes the flexion/adduction test, the internal rotation/external rotation

test, and the positive impingement test (Konin, Wilksten et al. 2006; Nussbaumer, Leunig et al. 2010).

Martin and colleagues (2010) investigated which physical exams are most frequently used by surgeons and hip specialists when treating hip disorders in adults. They found that the positive impingement tests (flexion/adduction/internal rotation) was done in 70% of visits, internal rotation with a fully flexed hip was done 98% of the time, external rotation with the hip flexed was done 86% of the time, and the flexion/adduction test (also known as the hip scour test) are most commonly used. Nussbaumer and colleagues (2010) tested the validity of these physical exams and found that the above physical exams had good test-retest reliability with high intraclass correlation coefficients (ICC) for all types of ROM when using a goniometer as the measurement tool. Hip Flexion had an ICC of 0.92, abduction was 0.92, adduction was 0.84, external rotation was 0.91, and internal rotation was the highest at 0.95. Excellent intra-rater reliability for all ROM physical exams has been demonstrated, with hip flexion ICC of 0.95, internal rotation 0.88, external rotation 0.85, abduction 0.85, and adduction 0.88 (Prather, Harris-Hayes et al. 2010). Lastly, it has been reported that researchers performing physical examinations can reliably differentiate FAI hips from healthy hips by using hip flexion ROM and internal rotation ROM tests. One study found a mean-absolute difference of five degrees for hip flexion, and seven degrees for internal rotation among testers. They also reported average values for hip flexion and internal rotation ROM physical exams, with max ROM of 127° and 31° respectively (Ratzlaff, 2013).

The positive impingement test is an important test used to specifically assess FAI, and was found to accurately diagnose 90% of patients with FAI (Dooley 2008). However, some studies report strong numbers of sensitivity, specificity, and accuracy of the impingement tests ability to diagnose FAI, while others studies are less optimistic. One study (Troelsen, Mechlenburg et al. 2009) reported a low sensitivity (59%) and a high specificity (100%). However, this study had a small sample size (n=18) and was investigating acetabular labral tears, not specifically FAI. As the authors point out, despite the limitations, follow up examination with imaging is recommended to confirm a diagnosis given the uncertainty of performing only physical exams. Other studies have shown high sensitivities (0.88-0.99) when dealing exclusively with FAI (Clohisy, Keeney et al. 2005; Sink, Gralla et al. 2008; Philippon, Briggs et al. 2009; Prather, Harris-Hayes et al. 2010). Unfortunately, these studies did not address specificity values. The impingement test has been shown to have low inter-rater reliability 0.58 (Martin and Sekiya 2008), which means it may not be ideal for using in diagnosing FAI. While it is has the best diagnostic ability of all possible clinical tests (Troelsen, Mechlenburg et al. 2009), it is not recommended to be used as the main source for diagnosing, and it cannot adequately distinguish FAI from other hip problems, hence the need for imaging to confirm the cam deformity (Burgess 2011).

Limited hip internal rotation was one of the first physical tests associated with FAI. It was found that patients with high alpha angle (74°) also had significantly reduced internal rotation (<10°), whereas patients with low alpha angle (42°) had good internal rotation (>20°) (Notzli, Wyss et al. 2002). Similar results have been found by Hack et al. (2010). Tannast et al. (2007) also found decreases in range of motion (ROM) during physical exams for the FAI group.

Internal rotation angles were 11.7° for the FAI group, and 35° in the normal group. The FAI group also had a significantly lower maximum flexion angle of the hip, being able to only achieve 105° flexion, while the normal group could achieve 121° flexion (Tannast, Kubiak-Langer et al. 2007).

Qualitative Assessments

The goal of quantitative analysis in this study is to use physical measures and data to assess hip function of subjects with FAI. However, the definition of function varies greatly which means that certain qualitative measures are important as well. Originally developed to assess pain, stiffness and functionality of the arthritic knee or hip, The Western Ontario and McMaster University Osteoarthritis Index (WOMAC) is often used to evaluate hips affected by FAI (Bellamy, Buchanan et al. 1988; Leunig, Beaulé et al. 2009). A recent study validated the use of WOMAC for prearthritic disorders such as FAI (Rothenfluh, Reedwisch et al. 2008). Reduced WOMAC score has been observed in FAI patients (Kennedy, Lamontagne et al. 2009). The Hip disability and osteoarthritis outcome score, abbreviated as the HOOS questionnaire, also measures hip function and pain, and can be used as a tool to assess FAI (Nilsson, Lohmander et al. 2003). The HOOS contains questions answered on a Likert scale, and the results are normalised scores which are calculated for each of the five sub-categories; pain, symptoms, activities of daily living (ADL), sport and recreation, and quality of life. Each sub-category has demonstrated excellent test-retest reliability has been observed over a 1-2 week interval, with ICC's of 0.95, 0.90, 0.96, 0.84, and 0.92 respectively (Hinman, Dobson et al. 2014).

Quantitative Assessments

Kinematics and Kinetics of Activities of Daily Living

Femoroacetabular impingement can determinately affect a person's ability to perform ordinary everyday tasks as the condition progresses. Once it has reached the stage of labral and chondral damage, pain follows as a symptom. Pain at the joint and a restricted range of motion due to impingement are noticeable during common daily activities such as sitting in an office chair all day, climbing a flight of stairs, or excessive walking (Ganz, Parvizi et al. 2003; Crawford and Villar 2005; Leunig and Ganz 2005; Wisniewski and Grogg 2006; Laude, Boyer et al. 2007). As the disease progresses, a substantial decrease in the range of motion at the hip will occur and severely affect one's ability to effectively perform activities of daily living.

Dynamic ROM

Previous studies have investigated the passive ROM in unilateral symptomatic FAI subjects. Hips affected by FAI showed an average reduction nine degrees in flexion, four degrees in abduction, three degrees in adduction, four degrees in internal rotation and three degrees in external rotation when compared to healthy contralateral hips (Clohisy, Nunley et al. 2007; Philippon, Maxwell et al. 2007). Ito et al. (2004) measured passive ROM between asymptomatic FAI with controls. They performed passive ROM tasks and compared the ROM in affected hips of FAI subjects to unaffected hips of healthy controls. Their results showed

reductions in hip flexion, internal and external rotation and abduction for the impinged hips compared to the healthy contralateral hips.

Kennedy et al. (2009a) compared a cam FAI group to an age/BMI matched healthy control group during maximal dynamic ROM. The dynamic ROM was setup such that flexion/extension, abduction/adduction and internal/external rotation with the hip flexed at 90°, all were done with subjects holding onto a stabilization bar for the dynamic ROM trials. Significant differences were found between the two groups, with the FAI group showing reduced hip total transverse ROM by 10.3°, reduced hip total sagittal ROM by 9.6°, reduced peak hip abduction by 9.2°, and a reduced peak internal rotation of 4.5° and a reduced peak external rotations of 5.7°. Asymptomatic FAD participants have not been assessed in any of the studies. It would be of interest to evaluate the dynamic range of motion of this group since they have no symptoms and presumably at the early stage of FAI, to test if decreases in ROM follow.

Gait

Motion analysis of gait has always been a major point of interest in biomechanics. Several early study mapped out detailed descriptions of lower limb biomechanics for non-pathological gait (Winter 1983; Kadaba, Ramakrishnan et al. 1989; Kadaba, Ramakrishnan et al. 1990; Eng and Winter 1995; Mills and Barrett 2001; Bejek, Paroczai et al. 2006). When the subjects in our study perform the gait task, they will be instructed to walk at a self-selected pace. Kadaba et al. (1989) tested the test-retest repeatability of gait variables when participants walked at their natural or preferred speed, and found a high repeatability for the natural self-

selected pace. Furthermore, a Bejek et al. (2006) paper observed reduced motion at the hip joint, which lead to increased pelvic motion during a faster gait speed for people with hip OA, but this trend was not observed in healthy controls. With regards to FAI, it has been shown that people with FAI do not have different walking speeds than comparable healthy controls (Kennedy, Lamontagne et al. 2009). Several papers have found results that indicate hip ROM increases as walking speed increases (Crowinshield, Brand et al. 1978; Mockel, Perka et al. 2003; Miyoshi, Shirota et al. 2004; Bejek, Paroczai et al. 2006). Gait is a well-studied area of research, and several studies have laid the foundation for expected results in healthy normal walking populations and normal speeds. The maximal hip flexion angle ranges from 15° to 30° (Winter 1983; Mockel, Perka et al. 2003; Miyoshi, Shirota et al. 2004), and the maximal hip extension ranges from 5° to 11° (Winter 1983; Mockel, Perka et al. 2003; Miyoshi, Shirota et al. 2004; Lee, Zavarei et al. 2005). Both the maximum abduction and adduction angle during walking is 5° (Judge, Davis et al. 1996). The same study reported the expected hip kinematics in the transverse plane to be approximately 1° for external rotation and 7° for internal rotation (Judge, Davis et al. 1996). Pelvic kinematics have also been studied, and frontal pelvic ROM in healthy participants can reach a maximum of 10.2°, and 6.2° for sagittal pelvic ROM (Vink and Karssemeijer 1988; Smith, Lelas et al. 2002; Taylor, Goldie et al. 2004; Bejek, Paroczai et al. 2006).

There are three studies that have compared the kinematics and kinetics during level walking between unilateral cam FAI subjects and matched healthy controls (Kennedy, Lamontagne et al. 2009; Hunt, Gunether et al. 2013; Rylander, Shu et al. 2013). In the Kennedy study, the FAI group was found to have a lower peak hip abduction angle, a reduced hip total

frontal ROM, a slightly lower hip total sagittal ROM and less pelvic ROM in the frontal plane during level gait compared to the control group. Similarly, the Hunt study also found decreased hip extension and abduction, but also found decreased hip adduction in the sFAI group. Rylander found significantly reduced hip internal rotation and hip sagittal plane range of motion during walking when compared with controls.

Squat

Squatting is the task that requires the largest ROM for the lower limb. Several papers have assessed the expected normal ankle, knee, hip and pelvic kinematics and kinetics during loaded and unloaded squatting (Kawagoe, Tajima et al. 2000; Flanagan, Salem et al. 2003; Hemmerich, Brown et al. 2006; Manabe, Shimada et al. 2007; Hwang, Kim et al. 2009). Hemmerich et al (2006) described the mean maximum hip flexion angle during heels flat squat as $95^{\circ} \pm 27^{\circ}$. Of particular interest, Lamontagne et al. (2009) compared 15 subjects with cam FAI and 11 matched healthy controls. The participants were instructed to keep their feet shoulder width apart, and perform a maximal squat depth. The FAI group had a significantly lower sagittal pelvic ROM ($14.7^{\circ} \pm 8.4^{\circ}$) versus the control group ($24.2^{\circ} \pm 6.8^{\circ}$). They also were unable to achieve the same depth of squat, reaching only 41.5% of leg length, compared to 32.3% of leg length for the control group, where a lower percentage represents a deeper squat. However, no difference in hip angles at the maximal squat depth was observed between the FAI group and the control group.

Sit and Stand

Sitting from a standing position and standing from a sitting position are movements that require mostly hip flexion. Kennedy (2008) measured sagittal hip kinematics and kinetics between sFAI and a con group, as well as the same variables in the transverse and frontal plane. 3D pelvis angles were measured as well but no differences in hip kinematics and kinetics were found for any of the variables in all 3 planes measured. The only observed difference between the two groups was that the sFAI group had a high level of variability in frontal kinematics and sagittal kinetics for both the sitting and standing maneuvers. This suggests that the sFAI group may compensate for the pain and discomfort they feel by using different strategies when performing this task.

Stairs

Stair climbing is another important daily task to observe since it requires more demand than walking tasks. Stair climbing has the ability to highlight differences that might go unnoticed with gait analysis. It is therefore important to study stair climbing as the sFAI and FAD groups may have differences that will only appear during the stair climb. A maximum of one and a half times greater than level walking hip flexion moment in stair descent has been reported (Andriacchi, Andersson et al. 1980). Normal lower limb mechanics were first extensively described by McFadyen and Winter (1988), which provides the fundamentals of typical patterns of stair ascent and descent. In a recent study (Protopapadaki, Drechsler et al. 2007) using very similar motion analysis techniques it was shown that stair ascent produces

greater hip moments than stair descent, while both tasks still have greater hip moments than level walking. An analysis of stair climb is recommended to attempt to highlight any potential deficiencies in the sFAI and FAD group's ability to perform the task over the control group. To our knowledge, the only study that compared the biomechanics of the hip joint during stair tasks was by Rylander (2013). They found that the sFAI group had significantly reduced hip internal rotation and hip sagittal plane range of motion during stair climbing when compared with controls (Rylander, Shu et al. 2013).

In order to objectively evaluate the difference between three group cohorts, biomechanical assessment with joint kinematics and kinetics as well as EMG data is necessary. From this review of literature, we observe that no study has undertaken such an investigation. People with sFAI have been studied and found to have deficiencies with regard to passive and active ROM in all three planes, a lower peak hip abduction angle and reduced hip total frontal ROM during gait compared to controls. Furthermore, a reduction in maximal depth squat and reduced pelvic ROM has also been found. The nature of FAD lends itself to study because the lack of symptoms provide potential for subjects to have similar biomechanical outcomes as the control group, yet the physical bone deformity on the head of the femur may provide a restriction on their hip joint mechanics that affects their biomechanical outcomes. This study will provide important information on the differences between the FAD and sFAI group in terms of their biomechanical ability to perform daily functional tasks.

Muscle Strength and Activity at the Hip Joint

Surface electromyography (EMG) is used to determine muscle activation. Studying these activation patterns can be useful to assist in kinematic and kinetic analysis, by linking the actions of certain muscles with the outcomes of the motion. Basic EMG activation cannot directly be related to muscle force, however it does give potentially useful data about muscle co-contraction and synergies. When EMG is combined with kinematic and kinetic results, it produces a better overall picture of the biomechanical and neuromuscular contributions of movement (De Luca 1997).

It has been widely reported that FAI can cause kinematic variations. It is still not fully clear if the changes are caused by FAI or neuromuscular adaptations. Therefore it is possible that the symptoms of FAI, particularly pain caused by joint damage, may impede muscle function and therefore the lower-limb kinematics and kinetics. This possibility lends itself to studying EMG as a means to help resolve the potential effects of neuromuscular adaptations in FAI.

Casartelli and colleagues (2011) observed reduced hip muscle function in patients with FAI compared to matched controls. Subjects had surface EMG electrodes attached to their rectus femoris (RF) and tensor fascia latae (TFL) muscles and performed ROM exercises on a dynamometer. The FAI group had a significantly reduced ability to activate TFL muscle during hip flexion than a control group ($p=0.048$), however RF activation was comparable between controls and FAI subjects ($p=0.056$). Also, the FAI group had lower MVIC strength than controls for hip adduction ($p=0.003$), flexion ($p=0.004$), external rotation ($p=0.04$), and abduction

($p=0.03$). Hip internal rotation and extension did not differ between the FAI group and control group. This study did not measure EMG activity of the prime mover muscle involved in the abduction, gluteus medius, only the TFL and RF. Furthermore, EMG was collected during isometric contraction only. This makes it difficult to make concrete conclusions about muscle activity during ROM exercises, only about overall leg strength. While there is a correlation between lower limb strength and EMG activity of the muscles responsible for the motion, specific information with regards muscle activity of patients with FAI is still lacking and cannot be obtained directly from this study. A recent paper on the EMG of FAI patients found the sFAI group trending toward inhibition of the tensor fascia latae (TFL), gluteus maximums, and erector spinae, and observed over activation of the rectus femoris during squatting (Lamontagne, Mantovani et al. 2013). Given the Casartelli (2011) and Mantovani (2013) findings of potentially inhibited TFL in FAI patients, a major difference in muscular strategy for FAI patients may be decreased use of the TFL, a hip abductor. As mentioned above, reduced peak hip abduction and hip and pelvic ROM have been found in FAI patients while performing walking tasks and this could be due to TFL deficiencies.

Hip Joint Pain

Pain is neurological response to potential harmful stimulus. It can act as a protective mechanism by causing a reflexive retraction from the stimulus, thus preventing damage to the body. However, if pain becomes chronic, the nervous system adapts and becomes de-sensitized to the pain. Inhibition of the descending inhibitory pathways results and can lead to increased

intensity of pain, referred pain to uninjured areas, as well as changes in pain threshold (Kwon, Altin et al. 2013).

Hip pain is often associated with biomechanical deficiencies, especially in OA patients. Unlike FAI, OA patients have no potential mechanical restriction that may be responsible for observed kinematic and kinetics adaptations. Therefore these biomechanical adaptations in OA patients may be the result of hip pain or neuromuscular adaptations. One study observed a reduced stride length, reduced maximal flexion and extension in the OA hip, and reduced maximal contralateral hip range of motion (Ornetti, Laroche et al. 2011). Subjects with unilateral hip OA have asymmetrical kinematics on the contralateral lower-limb. (Miki, Sugano et al. 2004). Similarly, subjects with motion deficiencies during walking, such as reduced dynamic range of motion, peak, extension, and internal rotation moments also were associated with a significantly higher presence of OA, with more severe OA causing more severe gait abnormalities (Foucher, Schlink et al. 2012).

Hip abductor pain induced by hypertonic saline solution in the gluteus medius can lead to reductions in hip abduction moments (Henriksen, Aaboe et al. 2009). Intra-articular hyaluronic acid injections at the hip joint have produced significant reductions in pain (as measured with visual analog scale). A significant improvement was noted regarding stiffness and disability, as measured by the WOMAC index, and patients walked with higher cadence and stride length after 6 months of treatment. Furthermore, after 6 months of treatment there were significant increases for the pelvic tilt at heel contact and hip flexion–extension moment at loading response sub-phases of gait cycle (Paoloni, Di Sante et al. 2012).

Individuals with asymptomatic cam deformity and limited internal rotation of $<20^\circ$ tend to develop hip pain over time when compared to people without cam deformity and normal internal rotation (Khanna, Caragianis et al. 2014). Following corrective surgery for FAI, there has been some limited success in return to normal biomechanics (Lamontagne, Brisson et al. 2011; Brisson, Lamontagne et al. 2013). However, it is not clear if this is a result of the correction of the hip joint damage, or the reduction in pain as both outcomes were reported. Also, there is a high amount of muscular damage associated with surgery, and the lack of overwhelming results with regard to post surgery improvement may be a result of subjects have not had enough time or proper post-surgery therapy to return to normal.

All these studies suggest the possibility the hip pain associated with intra-articular hip joint damage, as seen in OA, may be responsible for gait abnormalities. This further suggests that in FAI, a similar condition that has been linked to OA as a precursor disease, that pain may also be responsible for motion limitations.

Limitations

There are various limitations inherent in all biomechanical studies dealing with living human participants. All internal measures must be calculated indirectly by minimally invasive means. Joint kinematics are determined by external markers attached to the skin. Any movements of the skin or clothing which are independent of the underlying bone result in skin or clothing artifacts (Leardini, Chiari et al. 2005). These artifacts can produce relatively large errors, and vary widely between participants (Reinschmidt, van den Bogert et al. 1997).

Another limitation to the accuracy of kinematic data is the determination of joint centres. Joint centre locations are essential to determining angular kinematics, and are also calculated based on marker placements. Joint centres are dependent on personal anatomy, but general algorithms with personal anthropometric data inputs are standard in biomechanical research (Camomilla, Cereatti et al. 2006). Bone articulations at joints are further assumed to be frictionless. As with any generalized equations dealing with human anatomy, there is a margin of error. Finally, any marker misplacements by the researchers culminate these potential errors (Della Croce, Leardini et al. 2005). All these factors also limit the accuracy of kinetic data which is determined using the calculated kinematic information coupled with general segment parameter assumptions, and ground reaction force data. These factors and assumptions are intrinsic to all optoelectronic kinematic and kinetic research which use external markers, and limit the accuracy of the data acquired.

Further limitations specific to this study are the relatively small sample size of 51 participants (16 sFAI, 18 FAD, and 17 control), and the number of potential confounding variables which could affect results. Age, sex, weight, height, fitness level, flexibility, level of impingement, and type of impingement can all influence biomechanics. These variables will be measured and accounted for, but this high number of possible covariates with a small sample size may limit the level to which the results may be generalized to the total population.

Research Question

The overall question of this study was to determine whether there are differences in hip biomechanics amongst participants diagnosed with symptomatic (sFAI) and asymptomatic (FAD) femoroacetabular impingement and an age and BMI matched healthy control group during simulated daily activities. If both FAD and sFAI share the similar hip deformity, yet sFAI suffer pain, do differences in biomechanical variables exist between the two groups? Does the FAD have the same deficiencies that sFAI have as found in previous studies? Do differences in the same variables exist between FAD and a group of healthy controls?

Hypothesis

According to previous studies the following hypotheses have been drawn:

- 1.** The sFAI and FAD group would have significantly lower peak hip abduction angle and less total frontal and total sagittal hip ROM during the walking task than the CON group.
- 2.** The sFAI group and FAD group would show significant differences in total pelvic sagittal ROM during squatting as compared with the CON. An observed difference in maximal squat depth is also expected between sFAI and FAD when compared to CON.

3. The Internal and external rotation physical exams, and hip flexion test, will show significant angle deficiencies by the sFAI and FAD groups during the physical examinations, but not the CON group.

Rational

Since the hip joint is vital in locomotion, standing upright, and performing many daily activities, it is important to determine how hip deformity at the femoral head impacts in hip function. Understanding what types of movements are affected, and to what extent, will help in diagnosis of FAI, as well as in determining what movements should be avoided to prevent exacerbation. An early diagnosis and treatment of FAI is important since it may prevent the development of OA (Guanche and Bare 2006). Femoroacetabular deformity does not always manifest as symptomatic pain. An individual may technically have a positive diagnosis test for FAI from a radiograph or MRI, yet lack any further symptoms such as pain and stiffness and limited mobility. A study by Hack (2008) revealed that 26% of these asymptomatic FAI (FAD) individuals had a cam FAI deformity. To date, to our knowledge, there has been no study that compares the differences in hip joint biomechanics between FAD and sFAI individuals to healthy control (CON) participants. Therefore, the proposed study will measure the three-dimensional (3D) biomechanics of the hip, knee and ankle and the pelvis during maximal dynamic ROM, and during the activities of daily living (squat, walk) for FAD, sFAI, and CON participants.

Methods

Participants

A group of asymptomatic FAI participants (FAD) was compared to a group of symptomatic FAI participants (sFAI), and age, sex and BMI matched healthy participants (CON). The FAD participants had a positive diagnosis of cam deformity using axial and radial CT scan sequences. The axial view of the CT scan requires an α -angle greater than 50.5° (Notzli, Wyss et al. 2002; Hack, Diprimio et al. 2009) in order to identify bone deformity which could cause FAI. A second CT view, the radial view, requires an alpha angle greater than 60° (Rakhra, Sheikh et al. 2009; Sutter, Dietrich et al. 2012). A positive diagnosis in either view was considered asymptomatic, and a negative diagnosis in both axial and radial was required to be considered a control. To better appreciate the difference between CON and FAD participants due to the effect of the anatomical deformity, the side of interest for CON was the one showing the smaller axial-radial combined alpha angle. The affected side for FAD was the side with the greater combined alpha angle. In cases that both hips showed signs of FAI, the side with the larger deformity was chosen as the affected side. Participants were also tested to make sure they did not have pincer type FAI as well, which can be observed in the CT scan results as acetabular over coverage, in order to isolate for cam FAI only. Previous imaging studies have found intra-reliability sources of error when measuring alpha angle (Notzli, Wyss et al. 2002), and given these we implemented a “grey zone” in which if subjects fell into a range of $\pm 2.5^\circ$ of the axial and radial cutoffs, they were excluded because they could not convincingly be determined to be part of either the CON or FAD group. The sFAI group are in the ‘active cartilage damage stage’ which means they have a positive FAI diagnosis, as well hip pain longer

than 6 months near the groin/lateral aspect of the hip, a positive impingement test and AP radiographic evidence of deformity with an absence of arthritis and dysplasia. Participants in the CON group had no history of serious lower limb injury or surgery, and were recruited in part from the prevalence study by Hack (2009) that found they had a normal spherical femoral head neck contour, and some were recruited via the community through the Ottawa Hospital. The FAD participants were recruited through the Ottawa hospital as well. The sFAI group was recruited through the Ottawa Hospital after they presented signs of positive impingement test and visible cam morphology on CT scans. Participants were excluded from all three groups if hip OA was visible on the radiographs if they had substantial hip joint space narrowing, which is a sign of arthritis. Based on patient availability and the target group for study of cam FAI, only males were collected and matched with age-weight matched controls.

All participants were recruited registered through the Ottawa Hospital, and all scans administered by experimenters from the joint study at the Ottawa Hospital. Both the Ottawa Hospital Research Ethics Board and the University of Ottawa Health Sciences and Science Research Ethics Board approved the study protocol.

Materials/Equipment

Motion analysis was achieved by using ten infrared Vicon MX-13 cameras (VICON, Oxford, UK) in conjunction with reflective markers. The trajectory of the reflective markers was collected at 200 Hz and recorded using Vicon Nexus (version 1.7) software. Two Bertec force plates are built into a level walkway in such a way that the top of the surfaces are even with the

floor. The force plates are positioned staggered side-by-side to allow for the calculation of hip kinetics for each leg independently in the sit-to-stand and squat trials (models FP4060-08, Bertec Corporation, Columbus OH). Two mobile Kistler (models 9286BA, Kistler Instruments Corp, Winterhur, Swtz) force plates are built into the same walkway, and are moved onto a portable stair rig for stair ascent and descent trials. All force plates recorded ground reaction forces at 1000 Hz.

Skin tight black shorts and short sleeve lycra outfits were worn by participants (Appendix B). Using the UOMAM marker placement guidelines, 45 retro-reflective markers with a diameter of 14mm were attached to the participant (Appendix C). Large velcro patches are attached to the clothing in places where reflective markers go, and double sided tape is used to attach the reflective markers on areas where skin was exposed. The purpose of these skin-tight suits was to minimize the large errors caused by loose clothing.

EMG electrodes were attached to the following bilateral muscle groups using a 16 channel EMG system (FreeEMG 300, BTS BioEngineering, Milan, Italy): rectus abdominus, erector spinae, gluteus maximus, gluteus medius, rectus femoris, tensor fascia latae, biceps femoris, and semitendinosis. The precise placement is based on the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) (Hermens, Freriks et al. 2000). A second EMG system was used in a nine data collection sessions due to connectivity issues with the wireless BTS system (Delsys DS-B04 Bagnoli-16, Delsys Inc., Boston, MA).

An adjustable sit and reach flexibility test (Model 01285A, Lafayette Instrument, Lafayette, IN) was used to quantify participant flexibility. For isometric muscle strength, a Hand-

Held Dynamometer (HHD) (Model 01163, Lafayette Instrument, Lafayette, IN) recorded force values for maximal voluntary isometric muscle contraction (MVIC) in 5 lower-limb positions. The use of a hand-held dynamometer for protocol with similar leg positions has been shown to have good to excellent intrarater reliability (Krause, Schlagel et al. 2007; Pua, Wrigley et al. 2008). During the physical examinations, a goniometer measured angles such as hip flexion, internal and external rotation. During the MVIC's, the participant was in a laying down position on a physician's bench that has a strap across the support beams at the end. The strap was tightened and used to restrict the movement of the limb and hold it in place during the MVIC, such that isometric movements were performed.

A support frame was used to aid participants in performing dynamic hip range of motion trials (Appendix D). For the daily living tasks, a height adjustable bench was used for the sit-to-stand, the stand-to-sit, and the maximal squat depth tasks (Appendix E). It was placed directly in front of the two bertec force plates in the center of the walkway, in view of all the cameras. When stair trials were performed, the Kistler force plates were mounted on the first and second stairs of a custom-made three stairs setup with side rails (Appendix F). Each step has the same dimensions, a height and depth of 17.8 cm and 28 cm, respectively.

Protocol

Prior to meeting with the participant, a calibration of the Vicon system was performed. First, the dynamic calibration required waiving a T-shaped wand equipped with three 14mm retro-reflective markers (Appendix G) in the camera volume. The purpose of this calibration procedure is to configure each camera's position in space as well as their lens properties. The

dynamic calibration is complete when all of the MX cameras have captured a minimum of 6000 frames in which all three wand-markers are visible, and done with minimal image error, ideally below 0.1. Second, a static calibration with an L-shaped frame (Appendix H) sets the origin of the global coordinate system. The force plates will be turned on to warm up well before the trials start in order to prevent signal drifting. The EMG system will be charged the night before to make sure it has a full battery life.

The participant was met at the hospital for the CT scan. Prior to the CT scan the approved University of Ottawa Health Sciences and Science Research Ethics Board consent form was read and signed. The patient was asked to change into the provided hospital gown, and a CT technician administered the scan. Following the CT scan, the participant changed out of the gown and traveled to the motion analysis lab for the rest of the testing protocol.

Upon arrival, the participant filled out the WOMAC and HOOS questionnaires. Participates then changed into a black lycra suit followed by a five-minute warm-up exercise consisting of stretching their hamstring, quadriceps, hip adductors and gluteus maximus muscle groups, as well jumping jacks. Three trials of the maximal sit and reach flexibility test were performed. The sit-and-reach flexibility test was used to quantify patient hip and low back flexibility, since it can be a potential confounding variable that can affect biomechanics. The test has been found to have good reliability (0.9) (Martin, Jackson et al. 1998).

The anthropomorphic measures, listed in Appendix A, required for the UOMAM model were measured and recorded. Then, using a goniometer, physical examinations were performed. Researchers were blinded to the CON/FAD status of the subjects. Internal and

external rotation angle was measured by having the participant lay on their back, with the hip and knee bent at 90° as the examiner moves the shank medially (external rotation) and laterally (internal rotation). For hip flexion, the patient stayed on their back with the knee bent, as the examiner pushed their leg back in the flexed position. These measures are done for both legs. It is important to ensure the patient's pelvis stayed rigid during these measures so they don't influence the angles to cause greater hip flexion. The straight leg raise (SLR) test involves the participant raising one leg at a time, keeping the knee straight, as the examiner pushed back on the participant. The purpose of the test is to quantify low back function as it can be a potential confounding variable when assessing hip biomechanics. The literature states there is excellent intra-rater reliability and test-retest reliability which justifies the use of the physical exams (Nussbaumer, Leunig et al. 2010; Prather, Harris-Hayes et al. 2010). Using the SENIAM guidelines, the 16 EMG electrodes were placed over the surface muscles of the participant. Alcohol swabs were used to rub the area before the electrodes are placed, in order to reduce the impedance between skin and probes. If necessary, a safety razor will be used to shave the area. EMG was collected but not analyzed any further, as it was beyond the scope of the thesis. It will be used and analyzed in future studies.

The MVIC's for each muscle group were recorded next. The patient laid on the physicians table for each MVIC. For quadriceps muscle, TFL, gluteus medius MVIC motions, the participants laid on their back were instructed to keep the knee straight and move their leg at the hip joint only. This is so that specific hip muscles are isolated and not influenced by other lower leg muscles. The HHD was held stationary at their ankle as they push against it as hard as possible. As they performed the MVIC, the examiners used verbal encouragement in order to

attain the highest possible MVIC. For the same reason, participants are permitted to hold on the sides of the bed in order to create a stronger force and isolate the muscle and prevent a whole body contraction. Quadriceps muscles were isolated with a hip flexion movement, gluteus medius used a hip abduction motion, and TRL used a flexion/abduction movement at 45°. For gluteus maximus and the hamstring MVIC's, the participant laid on the front, and did a straight leg extension and knee flexion at 45°.

Following the MVIC protocol, retro-reflective markers were attached to the participant in accordance with the UOMAM model. A static trial was done while the subject, with one foot on each Bertec force plate, poses with their arms raised and facing out anteriorly to avoid concealing markers.

The participants performed a series of four different dynamic ROM trials. The examiner demonstrated the motion to the participant, and then let the participant practice the motion until they were adept at doing it, before the trials were recorded. Standing upright and holding onto the support frame with both hands, participants performed five continuous maximum trials for each of the ROM tasks. The ROM tasks are hip flexion and extension, hip abduction and adduction, knee internal and external rotation, and circumduction of the hip. The participants were instructed to keep the pelvis as stationary as possible while doing the ROM tasks to minimize pelvis tilt. All of these motions were repeated five times, for both legs, in a random order. However, the dynamic ROM tasks were not analyzed any further, only collected for future use.

The activities of daily living tasks were randomized for each participant to reduce any effect that may be caused by fatigue. As mentioned previously, the activities of daily living for this study consist of walking, squatting, sit-to-stand and stand-to-sit, and stair ascent and descent. All tasks will be performed at a self-selected speed in order to control for potential biomechanical differences caused by varying speeds.

For the walking trials, several practice trials were performed in order for the participant to get comfortable with the task. They were instructed to walk at a natural self-selected speed, (Crowinshield, Brand et al. 1978; Mockel, Perka et al. 2003; Bejek, Paroczai et al. 2006) keeping their head up and attempting to step completely on the force platforms in the middle of the walkway. Practice trials were repeated until the participant is able to consistently strike the force platforms naturally, without purposely targeting the platforms by adjusting their stride length. Each participant then performed five successful walking trials with one foot landing on a Kistler force plate followed by the other foot landing on a Bertec force plate.

The sit-to-stand and stand-to-sit task uses the two adjacent Bertec force plates and the adjustable bench. To perform these tasks, the participants stood approximately 10 cm in front of the bench with feet shoulder width apart and one foot on each force plate. Before any sitting or standing trials were collected, the bench was adjusted to the participant's tibial plateau height, collected previously during the anthropomorphic measures (Fleckenstein, Kirby et al. 1988; Arborelius, Wretenberg et al. 1992; Yamada and Demura 2004). The participant was instructed to sit down so the edge of the bench lined up in the middle of their thigh. The participants raised their arms slightly so they do not conceal any retro-reflective markers, and starting in the standing position, they sat down. Keeping their arms outstretched, the

participant stood up and completed five trials. Keeping the arms raised also helps prevent the participant from using them for support. Throughout the trial, the participant was instructed to keep their feet flat on the ground, without raising their heels at any point. All participants performed five sit-to-stand and five stand-to-sit trials. However, the sit-stand task was not analyzed for the thesis, the data was only collected for future use.

The bench used in the previous stage was lowered to $\frac{1}{3}$ of tibial plateau height for the maximal depth squat (Lamontagne, Kennedy et al. 2009). The bench also can act as a safety mechanism in case the participant loses balance or falls back. Participants began in an upright standing position 10 cm in front of the bench, standing with one foot on each force plate, with their feet at shoulder width, and their arms extended anteriorly to increase balance and prevent temptation to use them during the squat. Using a self-selected, controlled pace, they were instructed to squat down to their maximal depth without putting weight on the bench, until their buttocks lightly touches the bench, and then ascend back to standing position. This was repeated five times. During the squat, their heels remained on the ground, and any significant amount of weight off the bench when they achieve the lowest point of the squat and their buttocks is touching the bench. This is done to make sure they do not use the bench as a seat, but only as a guide for depth. If these conditions are not met trials were restarted until five good ones are collected.

Finally, the last task was stair ascent and descent. This task required participants to ascend and descend the stairs at their own pace without using the handrail, which is present for support in case of a fall. For stair ascent participants took one step on the ground before they step onto the first stair. They ascended up the stairs to the landing platform and took one step

forward on the flat surface. Ten trials will be recorded, five of which the participant starts with the left foot first and five starting with the right foot. To descend the stairs, they started on the edge of the landing platform, and their first step was onto the top stair. The second step was on the bottom stair and as they reach the ground they will continue to take a few steps forward away from the stairs. Ten trials were recorded, five of which the participant starts with the left foot first and five starting with the right foot. However, for the thesis the stair task will not be analyzed any further, merely collected for future use.

Data Processing and Analysis

Kinetics and kinematics from the sFAI and FAD groups were compared to controls to test for differences in key variables. The gait cycle was foot strike to foot strike for the affected side. For the squat task, decrease in hip flexion angle marks the beginning of the time cycle, and a maximum depth is measured by the lowest point of the posterior superior iliac spine (PSIS) marker during peak depth. Stable hip flexion angle following the ascent up marks the end of the cycle. Stair ascent/descent, sit-stand, and dynamic ROM tasks were all collected but not processed for the thesis.

The recorded 3-D coordinates of the retro-reflective markers were filtered by a Woltring filter (Woltring 1986) (predicted mean square error value of 15 mm^2) and the analog force plate data were filtered by an 8 Hz, dual-pass fourth order low pass butterworth filter. The UOMAM model was used to obtain the relevant kinetic and kinematic variables. Custom Matlab software

(Natick, Massachusetts, United States) was used to average the data and find maximum and minimum peaks of the dependant variables.

Kinematic Analysis

The level walking and squat tasks used five trials averaged for each participant. Joint ROM and peak joint angles are measured in two planes of motion (sagittal and frontal) for the hip, knee and ankle joints. The trials were ensemble-averaged to allow comparison of the FAD to the sFAI and CON groups. The kinematic dependent variables that were analyzed are shown in Table 1.

Kinetic Analysis

Kinetic data were calculated using inverse dynamics, which uses known forces and moments at the distal joint of a segment, in addition to the segment's motion and inertial properties, to calculate the forces and moments at the proximal joint of the segment. The values for each variable were averaged for the trials of each participant and then ensemble-averaged to allow comparison of the FAD group to the sFAI and control groups. Dependant variables that were examined from the calculated kinetics data are listed in Table 1.

Table 1 - List of dependant variables that were analysed.

Tasks	Analysis Type	Description (unit)
Walking Squat	Kinematics	Pelvic range of motion (°)
		Hip range of motion (°)
		Peak hip angles in each plane (°)
		Knee range of motion (°)
	Peak knee angles in each plane (°)	
	Ankle range of motion (°)	
	Peak ankle angles in each plane (°)	
Kinetics	Peak hip, knee, and ankle moments of force (Nm/Kg)	
	Peak hip, knee, and ankle powers (W/Kg)	

Statistical Analysis

One-way between-subjects ANOVAs were used to test for significant differences between all three groups for all dependent variables, and bonferroni adjustments were made ($\alpha = 0.025$). If significant differences were found in any of the ANOVAs, appropriate post hoc analyses was conducted. For the WOMAC assessments, the Kruskal-Wallis non-parametric test was used because the data was not normally distributed and was based on an ordinal scale. For all statistical analyses, SPSS 19.0 software was used (IBM Corporation, Armonk, New York, USA).

ARTICLE 1

BIOMECHANICAL COMPARISON OF PARTICIPANTS AFFECTED BY CAM FEMOROACETABULAR DEFORMITY TO SYMPTOMATIC FAI AND CONTROLS DURING FUNCTIONAL SQUATTING TASKS AND PHYSICAL EXAMINATIONS

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ABSTRACT

Femoroacetabular impingement (FAI) is a condition that is associated with hip joint deformity, causing joint pain and reduced range of motion. It is not known whether the biomechanical deficiencies are caused by the mechanical impingement itself or neuromuscular adaptations associated with pain and soft tissue damage. The aim of this study was to evaluate kinematic and kinetic differences between symptomatic FAI (sFAI), asymptomatic femoroacetabular cam deformity (FAD), and control (CON) groups during maximal depth squats and physical examination. It was hypothesized that the cam deformity would impinge at the acetabulum and femoral head during pelvic and hip motion in both sFAI and FAD groups. Fifty-one participants took part in the study but only 46 participants were retained in the analysis. Three groups were identified from their radiographic parameters: healthy controls, asymptomatic and symptomatic groups ($n = 46$; CON = 14, FAD = 17, sFAI = 15). Participants underwent common physical examination tests and performed non-weighted maximum depth squats while three-dimensional kinematics and kinetics results were collected and analyzed. Results demonstrated the sFAI group had significantly reduced internal rotation, external rotation, and a strong trend of reduced hip flexion angle compared to CON and FAD during physical examinations ($p = 0.037$, 0.001 , and 0.051 , respectively). In addition, physical exams indicated that internal rotation may be an effective predictor for FAD, as this group demonstrated reduced angles, but not significant, compared to the CON ($p = 0.069$). Interestingly, no statistical significance among groups was observed during squats; however, several trends were observed: Both the CON and FAD groups were able to squat deeper ($p = 0.082$), had greater pelvic range of motion ($p = 0.051$) and larger peak hip and knee flexion angles ($p = 0.19$ and 0.213 respectively) compared

to sFAI. These findings suggested that the bone deformity (FAD group) might not be directly related to restricting motion for the squat, and other cofactors such as soft tissue damage and muscular problems may be the cause, and should be the next avenue of study.

KEY WORDS: femoroacetabular impingement, FAI, squat, internal rotation, external rotation, hip, kinetics, kinematics

INTRODUCTION

Cam type femoroacetabular impingement (FAI) is an anatomic deformity characterized by an aspherical femoral head. It is a chronic hip disorder that causes hip pain, and reduces functional mobility and range of motion. It can lead to biomechanical variations (Lamontagne, Kennedy et al. 2009) during functional tasks, such as squatting, and is believed to be a possible cause of early osteoarthritis (Harris 1986; Ito, Minka et al. 2001; Ganz, Parvizi et al. 2003; Leunig and Ganz 2005).

The cam deformity is located at the anterosuperior aspect of the femoral head of the hip joint, and can be measured by alpha angle (AA) (Notzli, Wyss et al. 2002). Patients often complain of pain and physical impingement that hinders range of motion, typically preventing the person from participating in sports. Cam FAI occurs mostly in young athletic males at a prevalence of 17% of the population (Gosvig, Jacobsen et al. 2008), but there has been studies that have observed as much as 26% of healthy volunteers have asymptomatic FAI (i.e. FAD) (Hack, Di Primio et al. 2010).

To date, several studies have evaluated the effects of FAI on the biomechanics of daily functional tasks. However, only one study has specifically looked at squatting. Lamontagne, Kennedy et al., (2009) previously reported that FAI participants had a restricted sagittal pelvic motion and squat depth when compared to age-, gender-, and body mass index (BMI) matched controls. The lack of sagittal pelvic ROM was attributed to the cam deformity making contact with the acetabulum during deep squat, thus causing the limited motion. The deep squat activity is an important component of various common daily activities, and has potential to help identify FAI. Squatting requires a large sagittal hip and pelvic ROM that most control participants, but few FAI patients can fully achieve, making it a potentially useful diagnostic exercise for FAI compared to more expensive medical techniques such as MRI or CT scans.

Diagnostic tools such as questionnaires and physical examinations can also be used to identify FAI patients. However, the cam deformity does not always lead to pathologic impingement, and targeting diagnosis for asymptomatic cam deformity is a desired objective. The Western Ontario and McMaster University Osteoarthritis Index (WOMAC) is often used to evaluate hips affected by FAI (Bellamy, Buchanan et al. 1988; Rothenfluh, Reedwisch et al. 2008; Leunig, Beaulé et al. 2009). A recent study found reduced WOMAC scores in FAI patients (Kennedy, Lamontagne et al. 2009). The Hip disability and Osteoarthritis and Outcome Score (HOOS) questionnaire also measures hip function and pain, and can assess FAI (Nilsson, Lohmander et al. 2003). Physical examinations are also useful at diagnosing FAI since subjects demonstrate decreased internal rotation and a reduced hip flexion angles compared to controls (Tannast, Kubiak-Langer et al. 2007). Given the typical location of the cam deformity at the antero-superior aspect, it is suggested that limited internal rotation is linked to FAI since the cam

deformity will make contact with the acetabulum during the motion, however, sufficient evidence still lacks in this domain.

It has been observed that FAI subjects have reductions in hip musculature strength compared to controls when doing maximum voluntary isometric contractions (MVIC's). Casartelli found strength reductions during hip flexion (26% reduction), hip adduction (28% reduction), external rotation (18% reduction), and hip abduction (11% reduction) (Casartelli, Maffiuletti et al. 2011).

What remains unknown is whether biomechanical variations are due to mechanical impingement or the result of soft tissue damage and pain, followed by neuromuscular adaptations. It is often speculated in studies that the cam deformity is responsible for the observed impairments of the FAI hips, due to abutment of the femoral neck with the acetabular rim during motion requiring large range of motion. However, no known studies have studied dynamic motion for an asymptomatic cam deformity population - individuals who have similar anatomical deformities yet lack any pain or noticeable physical limitations. By analyzing two separate cam deformity groups, asymptomatic and symptomatic, along with a healthy control group, it will be possible to distinguish the effects of the cam deformity from the effects of the pain and soft tissue damage in squatting tasks and physical examinations.

The purpose of this study was to compare the kinematics and kinetics of the hip, pelvis and knee during maximal depth squats amongst three distinct groups: symptomatic FAI (sFAI) participants who have the enlarged, aspherical femoral head, labral damage, and pain symptoms; femoroacetabular cam deformity (FAD) subjects who have the cam bone deformity at the femoral head-neck junction but show no symptoms of pain or clinical signs, and a control

group (CON) matched by age, gender and BMI. Furthermore, physical exam testing and WOMAC and HOOS qualitative assessments were evaluated to see if they could be effective predictors of cam deformity and useful tools to assess both asymptomatic cam deformity and FAI. It was hypothesized that the sFAI group would have similar reduced pelvic range of motion (ROM) and squat depth as was found previously, and internal rotation and hip flexion angles would be limited during physical exam testing. The FAD group will also have these biomechanical variations due to the cam deformity's interaction with the acetabulum causing motion deficiencies when doing deep squats and high range of motion movements of the physical examinations compared to CON.

MATERIALS AND METHODS

Participants

Initially, a total of fifty-one male participants were recruited in the three groups and distributed as follows: 17 in the CON group, 18 in the FAD group, and 16 in the sFAI. However, based on exclusion criteria our final participant numbers were 14 CON, 17 FAD, and 15 sFAI, as presented in Table 2. Study exclusion criteria included a history of a lower body injury (aside from chronic hip pain), lower limb surgery, and evidence of osteoarthritis or acetabular over coverage (pincer FAI). All participants underwent computed tomography (CT) scans. CT images were used to visually measure the alpha angles by assessing the degree of asphericity of the femoral head. This assessment was used to determine if participants qualified for the study and whether they were part of the control or femoroacetabular deformity groups. Prior to the CT scan results, the researchers were blinded as to the status of the participant. The alpha angle was measured for

each hip, by a trained musculoskeletal radiologist (RK). Values greater than 50.5° in the axial plane or greater than 60° in the radial plane was used as a threshold to characterize the cam deformity and add the participant to the FAD group (Notzli, Wyss et al. 2002; Rakhra, Sheikh et al. 2009). Previous imaging studies have found intra-reliability sources of error when measuring alpha angle (Notzli, Wyss et al. 2002), and given these we implemented a “grey zone”, a range of $\pm 2.5^\circ$ of the axial and radial cut-offs, that would excluded patients because they could not convincingly be determined to be part of either the CON or FAD group. Two participants fell into the grey zone and were excluded. Three participants, one from each group, were excluded because they were unable to achieve a normal squat, and had outlier results (> 2.5 STD) (Miller 1991) in a major kinematic variable such as squat depth, hip or knee flexion angle, and observed irregular squat form. All CON and FAD participants were recruited from the Ottawa region by the Ottawa Hospital through interaction with community members, and via a previous prevalence study (Hack, Diprimio et al. 2009). The sFAI group was recruited through the Ottawa Hospital after they presented signs of positive impingement test and visible cam morphology on CT scans.

This study was approved by the Ottawa Hospital Research Ethics Boards and the University of Ottawa Health Sciences and Sciences Research Ethics Board. All participants signed informed written consent prior to participating.

Table 2 – Participant demographics, with the mean and standard deviation (SD).

Variable	CON	FAD	sFAI
Participants	14	17	15
Age (Years)	32.8 (6.6)	31.1 (5.1)	39.5 (8.5)
BMI	26.2 (3.4)	25.8 (2.9)	27.6 (4.6)
Affected Axial AA (deg)	41 (4.7)	58 (9.5)	56 (8.7)
Affected Radial AA (deg)	49 (3.9)	67 (7.8)	64 (7.8)

Protocol

All participants underwent a CT scan at the Ottawa General Hospital to confirm their status as FAD or CON participant. The sFAI group had a follow-up MRI to determine the level of bone and tissue damage. Participants filled out WOMAC and HOOS questionnaires to evaluate perceived hip function and pain.

Following the CT scan, the participant was brought to the biomechanics laboratory for the experimental session. Since the CT scan results were not analyzed at this point, researchers were still blinded to the CON/FAD status of the subjects. First, physical exam testing was conducted. Participants lay on a physician's table while the researcher performed full ROM tests by applying pressure until resistance was felt or subject expressed pain. Motions included straight leg raise, sit-and-reach flexibility, internal rotation, and external rotation and hip flexion, all of which were measured using a goniometer. The sit-and-reach flexibility test and straight leg raise were used to quantify patient hip and low back flexibility, since it can be a potential confounding variable that can affect biomechanics. Authors have demonstrated a very good intra-rater reliability and test-retest reliability for the physical exams (Nussbaumer, Leunig et al. 2010; Prather, Harris-Hayes et al. 2010). Following this, MVIC testing was done as part of an electromyography (EMG) protocol. The EMG data was not further analyzed but the MVIC

strength testing was compared among the three groups. Two consecutive MVICs were performed for the following muscle groups/movements: Hip flexors, the rectus femoris, with the subject in a supine position, straight leg raise up to 15° in the sagittal plane and resistance at the ankle; Hip abductors, the gluteus medius, with the with the subject in a supine position, straight leg spreading up to 15° in the frontal plane and resistance at the ankle; Hip oblique, combination of flexors and abductors to study the tensor fascia latae muscle, with the subject supine, straight leg raising and abducting, and up to 15° in each plane, resistance at the ankle; Hip extensors, the gluteus maximus, with the subject in a prone position, straight leg raise up to 15° in the sagittal plane, resistance at the ankle; Knee flexors, the hamstrings, with the subject in a prone position, knee bent at 45° in the sagittal plane, resistance at the ankle. The MVIC strength was measured using a handheld dynamometer (Lafayette, IN), and the highest force output was used for analysis. Two studies have shown that hand-held dynamometers have good to excellent intrarater reliability, and that using this particular type of protocol is a reliable method to assess strength (Krause, Schlagel et al. 2007; Pua, Wrigley et al. 2008).

Next, dynamic motion trials were captured with ten Vicon MX-13 motion capture cameras (Vicon, Oxford Metrics, Oxford UK), at a collection frequency of 200 Hz, along with two Bertec forceplates (FP4060, Bertec Corp., Columbus, OH, USA) to measure ground reaction forces, at a collection frequency of 1000 Hz. A 45 retro-reflective full body marker set was used (McLean and Beaulieu 2010). The participants were instructed to do a maximal depth squat, keeping their feet flat on the ground and shoulder-width apart, squatting as low as possible without lifting their heels (Figure 1). A total of five squat trials were collected. The beginning of the squat cycle was defined by the initial hip flexion before the descent. The end of the squat

coincided with the final extended upright position after the ascent. The maximal depth was the instance where the subject was in full squat and the PSIS markers were at the lowest point.



Figure 1 – Example of a participant doing a maximal depth squat.

Data Analysis

To better appreciate the difference between CON and FAD participants due to the effect of the anatomical deformity, the side of interest for CON was the one showing the smaller axial-radial combined alpha angle. In cases that both hips showed signs of the cam deformity in the FAD group, the side with the larger deformity was chosen as the affected side. Participants also were tested to make sure they did not have pincer type FAI as well, which can be observed in the CT scan results as acetabular over coverage, in order to isolate for cam FAI only. In order to

calculate the moment of force for the MVIC strength testing, subject-specific anthropometric data (segment mass, inertia and center of mass) were computed according to modifications of the Zatsiorski-Seluyanov parameters by De Leva (de Leva 1996). The moment of force was calculated for each test by combining the anthropometric and force data. The results were normalized by body mass in order to allow inter-subject comparison. Muscle strength ratio for the sFAI group relative to the control group is characterized by calculating the percentage differences as such:

$$(MVIC_{sFAI} - MVIC_{CON}) / MVIC_{CON} * 100 \quad (1)$$

The same equation was applied to the FAD group relative to the CON group and for sFAI relative to FAD group.

Kinematic data for the leg of interest were computed using a modified plug-in-gait model (Beaulieu, Lamontagne et al. 2010) in Body Builder software (version 3.6.1, Vicon, Oxford, UK). Prior to computing the lower-limb kinematics, markers were labeled, filtered, and modeled using Vicon software. The surface marker trajectories were filtered using a Woltring filter (Woltring 1986) set at 15 MSE and force plate data was conditioned using a second order dual-low-pass Butterworth filter (8Hz).

Custom MATLAB software (MATLAB, The MathWorks, Inc., Natick, Massachusetts, USA) was used to extract the kinematics variables for each trials and ensemble average across participants for each group.

Dependant variables for the squat were: squat depth (quantified as a percentage of leg length, where 0% is floor level, and leg length is defined as the distance between the ASIS and medial

malleolus), peak hip flexion, peak knee flexion, pelvic ROM, and peak hip flexion moment. Dependant variables for the physical examinations were the ROM (expressed in degrees) for the following motions: straight leg raise, internal rotation, external rotation, hip flexion, and sit-and-reach flexibility. For the WOMAC and HOOS assessments, several different parameters were measured: HOOS pain, other symptoms, function in daily living, function in sport and recreation, hip related quality of life, WOMAC pain, stiffness, function, and total score. For each dependent kinematic variable, a one-way analysis of variance (ANOVA) was used to test for significant differences between groups with an alpha value of 0.05. For the WOMAC assessments, the Kruskal-Wallis non-parametric test was used. Statistical analysis was conducted with SPSS version 19 software (IBM Corporation, Armonk, New York, USA).

RESULTS

WOMAC and HOOS

Questionnaire results for all the HOOS and WOMAC parameters are presented in Table 3. Both assessments are graded out of a possible 100 points, where a higher score represents no impairment. For example, a higher WOMAC pain score correlates to less pain reported by the person. The Kruskal-Wallis test found significant differences for all parameters of both the WOMAC and HOOS questionnaires.

Pairwise post-hoc analysis using independent T-tests revealed that the sFAI had significantly reduced scores for every HOOS and WOMAC metric compared to FAD and CON groups ($p < 0.001$), while there was no significant difference between FAD and CON groups ($p > 0.100$) for all parameters.

Table 3 – Results for the WOMAC and HOOS questionnaire metrics, for the CON, FAD, and sFAI groups. (*) indicates a significant statistical difference between sFAI and CON groups, and (‡) indicates significant statistical difference between sFAI and FAD groups.

	CON	FAD	sFAI	p-value
	Mean (SD)	Mean (SD)	Mean (SD)	
HOOS Symptoms*‡	99.3 (1.8)	95.4 (8.2)	66.0 (15.9)	0.000
HOOS Pain*‡	99.1 (3.3)	98.4 (4.7)	64.2 (19.4)	0.000
HOOS ADL*‡	99.7 (1.2)	99.7 (1.2)	73.4 (19.4)	0.000
HOOS Sport and Rec*‡	98.2 (5.1)	97.3 (7.2)	52.1 (28.2)	0.000
HOOS QoL*‡	97.8 (8.4)	96.3 (8.7)	33.3 (21.6)	0.000
WOMAC Pain*‡	99.3 (2.7)	99.6 (1.3)	71.3 (20.0)	0.000
WOMAC Stiffness*‡	99.1 (3.3)	96.4 (9.1)	62.5 (22.7)	0.000
WOMAC Function*‡	99.7 (1.2)	99.7 (1.2)	73.4 (19.4)	0.000
WOMAC Total*‡	99.4 (1.7)	99.0 (2.0)	70.3 (19.3)	0.000

Physical Exam

A summary of the physical exam results is presented in Table 4. There were statistically significant differences between groups for external rotation and internal rotation ($p = 0.001$ and $p = 0.037$ respectively) and a trend for hip flexion ($p = 0.051$). Pairwise post-hoc analysis using independent T-tests revealed that the FAD and CON had no differences between any of the tests, however there was a trend that indicated the FAD had reduced internal rotation compared to the CON group ($p = 0.069$). The sFAI had significant decreases in external rotation when compared to the CON ($p = 0.001$) and FAD ($p = 0.002$) groups. The sFAI also had significant

decreases for internal rotation ($p=0.021$) and hip flexion ($p = 0.031$) when compared to the CON. There were no differences among the sit-and-reach flexibility of the groups ($p = 0.438$) or straight leg raise ($p = 0.360$) and thus it was not further analyzed as a co-factor.

Table 4 – Results from the physical exam tests, for affected sides of FAD, sFAI and CON groups. (*) indicates a significant statistical difference between sFAI and CON groups, and (‡) indicates significant statistical difference between sFAI and FAD groups.

	CON Mean (SD)	FAD Mean (SD)	sFAI Mean (SD)	P-value
Straight Leg Raise (deg)	95.6 (16.1)	94.4 (17.7)	87.1 (16.1)	0.360
External Rotation (deg)*‡	50.1 (13.3)	46.6 (10.9)	31.5 (12.5)	0.001
Internal Rotation (deg)*	39.9 (12.8)	30.8 (12.4)	24.9 (17.5)	0.037
Hip Flexion (deg)*	136.2 (8.8)	131.8 (8.9)	123.6 (15.9)	0.051
Flexibility (cm)	21.4 (10.6)	23.7 (11.8)	26.6 (10.1)	0.438

Kinematics and Kinetics of Squat

Group means and standard deviations of squat variables in the sagittal plane are presented in Table 5. There were no differences or trends for any frontal or transverse plane variables. For squat depth, the FAD and control groups were found to squat at a similar depth of 37.1% and 37.5% of leg length respectively while the sFAI group only reached 44.4%. However, between group differences in squat depth were not statistically significant ($p = 0.082$). The sagittal pelvic tilt ROM over the entire squat is displayed in Figure 2. The FAD and control groups both had a larger pelvic ROM than the sFAI group. The FAD and control groups performed their squat with 15.5° and 17.1° ROM respectively, while the sFAI group performed their squat with only 12.3°

ROM. The pelvic ROM for the three groups was not significantly different ($p = 0.051$). Hip flexion angle for the entire squat is displayed in Figure 3. Both the FAD and CON groups had a higher peak sagittal hip flexion angle than the sFAI group, with maximum flexion of angle of 109.1° and 105.9° for the CON and FAD groups, respectively. The sFAI group only attained 102.2° of hip flexion. No significant differences were found amongst the three groups ($p = 0.195$). Accordingly, the CON (129.1°) and FAD (128.1°) groups had higher peak knee flexion angles than the sFAI (119.5°), but again no significant differences were found ($p = 0.213$). For kinetics, the peak hip flexion moment was calculated but there was no significance between groups (Figure 4) ($p = 0.993$).

Table 5 – Results of key squat kinematic and kinetic variables for CON, FAD, and sFAI.

Variable	CON Mean (SD)	FAD Mean (SD)	sFAI Mean (SD)	p-value
Squat Depth (% of leg length)	37.1 (8.8)	37.5 (9.9)	44.4 (10.6)	0.082
Total Pelvic ROM (deg)	15.5 (6.3)	17.1 (6.0)	12.3 (3.6)	0.051
Peak Hip Flexion angle (deg)	109.1 (10.9)	106.0 (9.5)	102.2 (10.12)	0.195
Peak Knee Flexion angle (deg)	129.1 (14.1)	128.1 (17.3)	119.4 (16.8)	0.213
Peak Hip Flexion Moment (Nm/Kg)	-0.93 (0.2)	-0.92 (0.2)	-0.92 (0.2)	0.993

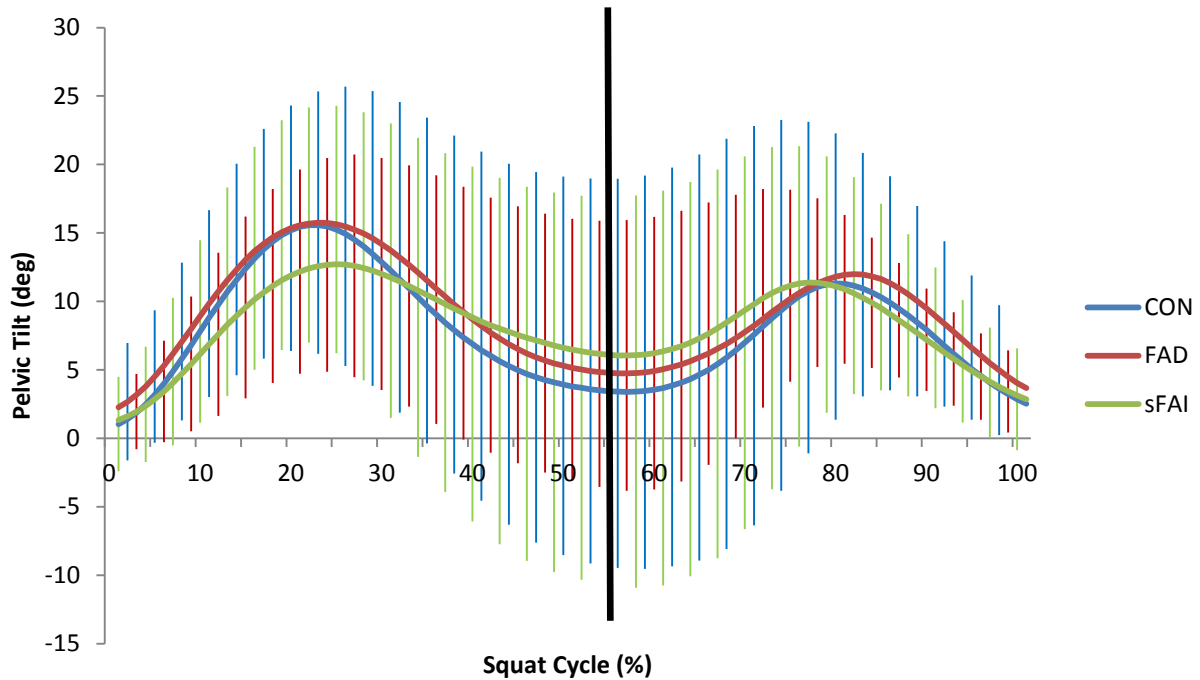


Figure 2 - Group means and standard deviations of pelvic tilt (deg) during maximal depth squat for FAD, sFAI and CON groups. The squat is time normalised such that 0% represents the beginning of the squat motion when the participant is standing upright, and 100% represents the end of the cycle when the participant has completed the squat and is again standing upright. The vertical black bar in the middle represents the maximal squat depth, which occurs at approximately 56% of the squat cycle.

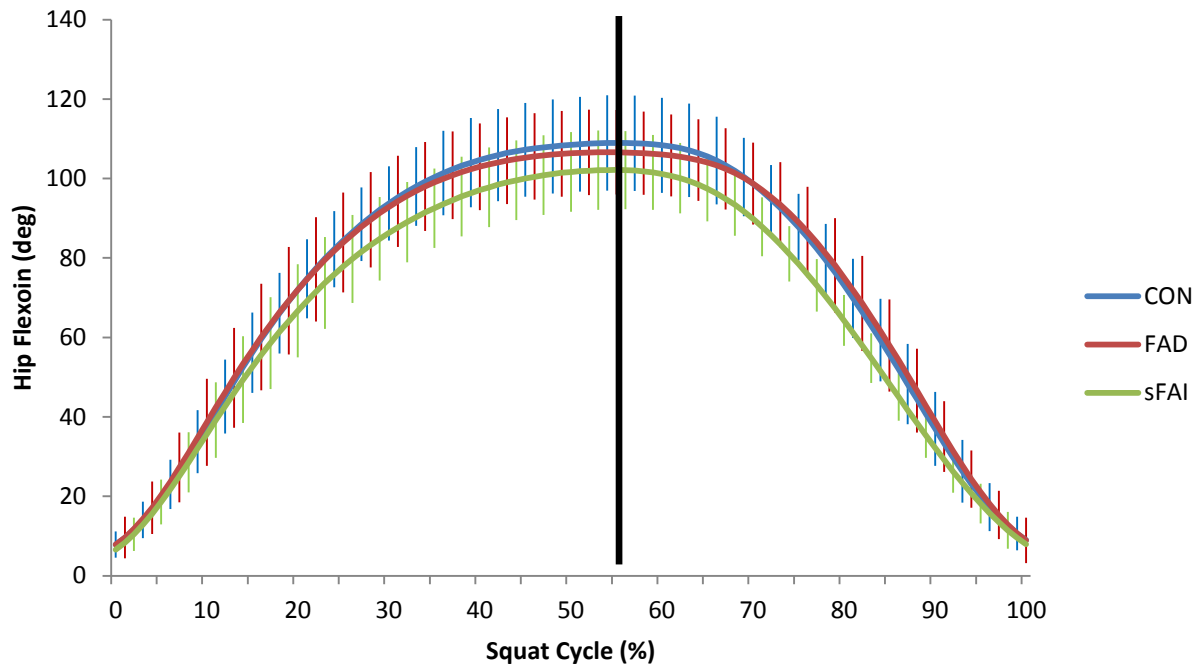


Figure 3 - Group means and standard deviations of hip flexion (deg) during maximal depth squat for FAD, sFAI and CON groups. The squat is time normalised such that 0% represents the beginning of the squat motion when the participant is standing upright, and 100% represents the end of the cycle when the participant has completed the squat and is again standing upright. The vertical black bar in the middle represents the maximal squat depth, which occurs at approximately 56% of the squat cycle.

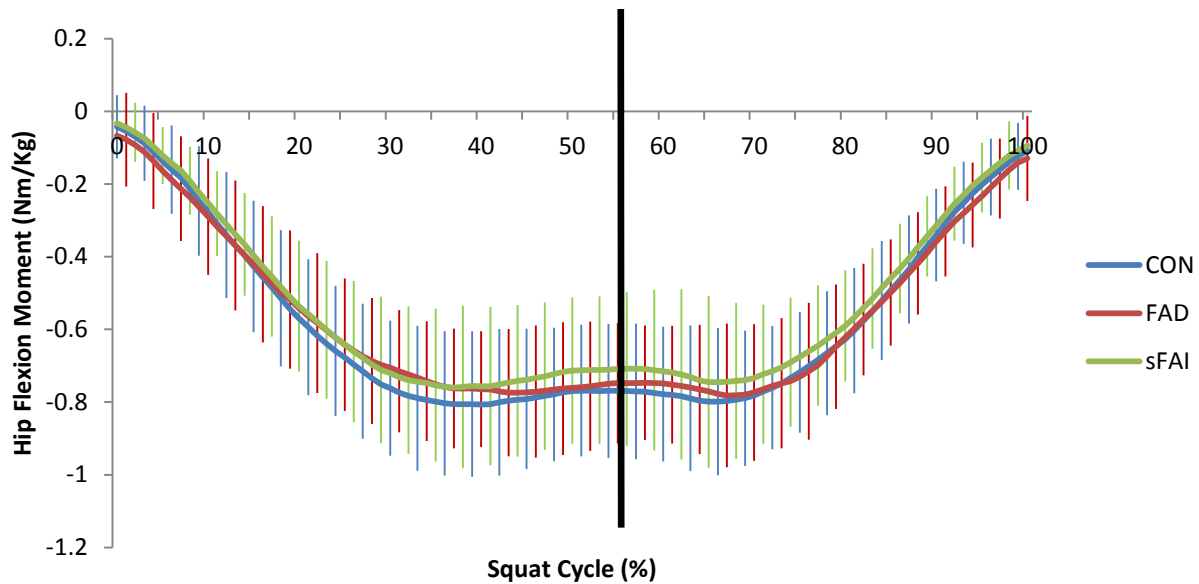


Figure 4 - Group means and standard deviations of hip flexion moment (Nm/Kg) during maximal depth squat for FAD, sFAI and CON groups. The squat is time normalised such that 0% represents the beginning of the squat motion when the participant is standing upright, and 100% represents the end of the cycle when the participant has completed the squat and is again standing upright. The vertical black bar in the middle represents the maximal squat depth, which occurs at approximately 56% of the squat cycle.

Maximal Voluntary Isometric Contraction Strength

Group means and standard deviations are present in Figure 5. There were no significant differences between groups for moment of force. Overall there appeared to be reductions in sFAI moment of force, as reported by 20%, 12%, 15%, and 11% decreases for the hip flexors, abductors, oblique, and extensors respectively. They sFAI group did report a 4% increase in knee flexion moment force. Compared to FAD, the sFAI had 20%, 14%, 13%, 20%, and 12% decreases in moment of force for the hip flexors, abductors, oblique, and extensors and knee flexors. For the hip flexors, abductors and obliques (TFL muscle) the FAD and CON had similar results, but for the hip extensors and knee flexors the FAD group had 11% and 19% increase in moment of force.

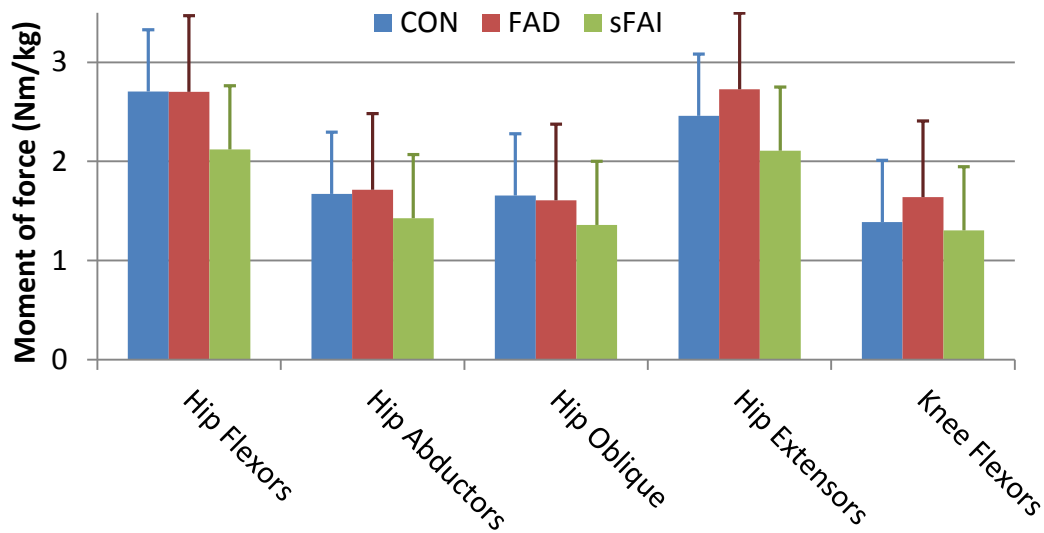


Figure 5 - Moments of force (Nm/kg) in each direction for CON, FAD and sFAI groups.

DISCUSSION

This study investigated kinematic and kinetic variations of maximal squat depths and physical examinations in FAD, sFAI, and CON groups. Based on previous studies (Lamontagne, Kennedy et al. 2009) it was hypothesized that both the sFAI and FAD would have reduced pelvic ROM and squat depth compared to the CON group as well as decreased internal rotation and hip flexion during physical exams. Our results do not support our hypotheses regarding the squat since we observed no significant differences in any of the hip kinematic or kinetic variables between groups. Our results for the physical exams partially support our hypothesis: we found decreased external and internal rotation and hip flexion for the sFAI compared to controls, and a strong trend indicating decreased internal rotation for the FAD group.

However, the squatting tasks did yield interesting trends that warrant discussion. Firstly, the CON group and FAD group demonstrated an ability to achieve greater squat depths, total pelvic ROM, and hip flexion angles when compared to the sFAI group ($p = 0.10, 0.053, 0.19$). Both the CON and FAD had more participants achieve a maximum squat (43 and 44% respectively); whereas the sFAI group only had 20% achieve a maximum squat. Secondly, these between group similarities were reflected in the reported WOMAC and HOOS pain scores, where FAD and CON had “low levels” of hip pain (99.29 and 99.64 for the WOMAC, 99.11 and 98.39 for the HOOS) and sFAI reported higher levels of pain (71.33 and 64.17 for the WOMAC and HOOS, respectively). All of the other WOMAC and HOOS parameters followed this pattern of FAD and CON having near equal and significantly higher scores than sFAI.

In accordance with our findings, previous work by Lamontagne et al (2009) found that the sFAI had significantly less squat depth and a decreased pelvic ROM than CON. Considering the similar squat depth, hip flexion angles and pelvic ROM between the FAD and CON group, it is plausible that the cam bone deformity does not cause major physical restriction during a maximal depth squat. The reduced squat depth in the sFAI group relative to the FAD suggests that the symptoms of FAI, such as pain and joint damage, is associated with the reduced squat depth, rather than the mechanical impingement of the cam deformity diagnosed by alpha angle.

Contrasting this notion, a more recent study by Lamontagne et al. (2011) evaluated squat depths after corrective surgery. The corrective surgery consisted of bone resection of the deformity at the junction of the femoral head and neck, and labral-chondral repair. One year

later, FAI patients showed an improvement of 3.7% in maximal squat depth, indicating the cam deformity indeed causes a mechanical impingement and reduced squat depth. However, patients also reported a significant reduction in the level of pain, so the root cause of FAI still remains unclear. When these results are taken into account with the results of this study, the better squat performance is likely related to the lack of pain post-surgery and not the clearance of the cam impingement.

The significantly decreased internal rotation and hip flexion of the sFAI compared to CON ($p = 0.021$, $p = 0.031$) is consistent with previous literature on physical examinations in FAI patients. A new finding from this study was that of decreased external rotation in sFAI compared to controls ($p = 0.001$) and FAD ($p = 0.002$). The research question was to assess the function of the asymptomatic FAD group, however; we observed no deficiencies relative to controls to suggest the cam deformity has little impact on pelvis and hip motion.

One of the key factors that helps diagnose FAI, and is almost always associated with FAI and large alpha angles, is a limited internal rotation (Notzli, Wyss et al. 2002; Rakhra, Sheikh et al. 2009). Although previous studies based this relationship on symptomatic subjects, a trend of reduced internal rotation was also observed in our FAD compared to CON. Internal rotation physical exam was a true maximum movement, with the researcher fully rotated the leg to its limit, while the rest of the body was in a passive relaxed position. The limited internal rotation is maybe due to the cam deformity, located at the anterosuperior aspect of the femoral head/neck region, thus making contact as the thigh internally rotates into the acetabulum. This

is the only observed parameter that distinguishes our FAD from sFAI, and can potentially be a predictive factor.

Previous literature reported decreases in hip flexion and abduction force for patients with FAI (Casartelli, Maffiuletti et al. 2011). Our study had a similar protocol but did not find statistically significance differences among groups. We found the sFAI group had decreased hip flexion (20%, $p = 0.166$) and abduction in the sFAI (12%, $p = 0.312$) compared to CON, and likewise also had decreased hip flexion (20%, $p = 0.166$) and abduction (14%, $p = 0.312$) compared to the FAD group, but not significantly different. Overall the CON and FAD groups had similar force moments except for an increased hip extensor moment of force in the FAD compared to CON. While the results indicate that no muscle weakness are present, it is possible that EMG analysis may detect other neuromuscular adaptations, such as muscle onset timing issues, and co-contraction, and is recommended as an area of future study.

Rather than a mechanical impingement, we suggest biomechanical discrepancies of sFAI are attributed to the presence of pain. Pain can be a major factor that can cause motion deficiencies (Henriksen, Aaboe et al. 2009). The WOMAC and HOOS questionnaires demonstrated that sFAI has pain, stiffness and reduced hip function not experienced by either the CON or FAD group. This is not surprising given the asymptomatic nature of FAD. In fact, participants were unaware of their FAD status until they had a CT scan.

One linking theory that supports all the results is the presence of pain. Pain is known to have inhibiting affects on motion. It has been found that hip abductor pain (induced by hypertonic saline solution in the gluteus medius) can lead to reductions in hip abduction moment

(Henriksen, Aaboe et al. 2009). Contrastingly, intra-articular hyaluronic acid injections at the hip joint have produced significant reductions in pain for people with OA. A significant improvement was noted regarding stiffness and disability, as measured by the WOMAC index, and patients walked with higher cadence and stride length after 6 months of treatment. Furthermore, after 6 months of treatment there were significant increases for the pelvic tilt at heel contact and hip flexion–extension moment at loading response sub-phases of gait cycle (Paoloni, Di Sante et al. 2012). Individuals with asymptomatic cam deformity and limited internal rotation of $<20^\circ$ tend to develop hip pain over time, compared to people without cam deformity and normal internal rotation (Khanna, Caragianis et al. 2014). This provides evidence that FAD participants are at a higher risk for developing pain symptoms. However, more study into whether these subjects have subsequent motion deficiencies and develop further symptoms such as labral tears would be beneficial to conclude whether FAD is at a higher risk for developing FAI.

To date, the root causes of FAI and its symptoms are unknown. Much of the research focuses on alpha angle as the main measurement for assessing FAI (Notzli, Wyss et al. 2002; Beaulé, Zaragoza et al. 2005; Tannast, Siebenrock et al. 2007; Leunig, Beaulé et al. 2009; Rakhra, Sheikh et al. 2009; Jung, Restrepo et al. 2011; Sutter, Dietrich et al. 2012), and it has been proposed that the cam deformity causes acetabular labral-chondral damage in patients with hip pain (Beaulé, O'Neill et al. 2009). However, our results found the FAD group fundamentally had the same biomechanics during squat as the control group despite the same deformity as the sFAI. Our physical exams found that the FAD and CON were similar in all categories, except for internal rotation, which showed a strong trend toward decreased angle in FAD, but not

statistical significance. This brings up two possible issues regarding classification: 1) the alpha angle and cam deformity is not effective in distinguishing FAD from sFAI since it cannot adequately characterize symptoms, and other geometric hip co-factors may be implicated in sFAI, or 2) the alpha angle is effective at diagnosing FAI, and the reason the sFAI group has biomechanical deficiencies is due to soft tissue degeneration and pain not found in FAD. Neither scenario discards the notion that cam deformity is a cause for developing symptoms, which is still a likely proposed mechanism, but rather excludes the bump deformity as a cause for impingement in motions during daily functional tasks such as squat.

In regards to the first issue, a recent study investigated other potential confounding hip deformity factors, such as femoral neck-shaft angle, femoral head-neck offset, femoral and acetabular versions. Using a discriminate function analysis it was observed that FAD have fairly normal femoral and acetabular versions when compared to controls (Ng, Lamontagne et al. 2013). However, the sFAI group had a significantly decreased femoral neck shaft angle and also notably reduced femoral head-neck offsets. This is an important finding that indicates perhaps the alpha angle may not be the main reason for mechanical impingement and biomechanical deficiencies, and other variables should be considered just as strongly. The next step would be to investigate these variables in the FAD population to see if they are associated with motion deficiencies.

The second possibility is that biomechanical deficiencies are due to soft tissue degeneration and pain and not a function of mechanical impingement as previously thought. Early theories and results indicated that mechanical impingement was the cause of the limited ROM in

functional motion tasks, specifically the abrasion caused by the aspherical femoral head contacting the acetabulum impeded the motion (Lamontagne, Kennedy et al. 2009; Lamontagne, Brisson et al. 2011; Hunt, Gunether et al. 2013). This constant abrasion of the abnormal contact between acetabulum and femoral head is still a possible cause of joint damage. However, it is more likely that soft tissue damage is responsible for the impeded motion in the squat and physical exams given our results. Large cam deformity (and therefore alpha angle) has been proposed as a mechanism for development of acetabular labral-condral damage in patients with hip pain (Beaule, O'Neill et al. 2009). In fact, studies show that the sFAI group often require surgical chondroplasty for the acetabular cartilage damage and labral repair (debridement) (Beaule, Zaragoza et al. 2005; Beaule, Hynes et al. 2012). The joint damage and soft tissue degeneration experienced by sFAI group is a very important consideration, and the biomechanical variations in the squat and physical exams can in part be explained by the presence of these factors. Truly the only way to determine if the cam deformity causes symptomatic FAI is to do a longitudinal study on the FAD subjects to see how many become symptomatic FAI.

There are limitations in this study. First, we restricted the height of squats to 1/3 of tibial height. We based this height on our previous work and tried to retain consistency with any previous results (Lamontagne, Kennedy et al. 2009). In theory, any potential restrictions of the FAD group may occur at deeper depths of the squat. Also, we did not analyze trunk kinematics, which may be an important consideration during the squat, since the upper body position will influence the squat strategy of the lower body, and therefore affect the lower body kinematics. Second, in the MVIC strength protocol we only performed two strength tests per muscle group.

Since participants were not familiar with the procedure ahead of time, they may not be able to produce high outputs or achieve their actual maximum contraction as a result of only have two MVIC attempts. Thirdly, there are inherent limitations to any study that calculates joint kinematics, due to marker misplacements (Della Croce, Leardini et al. 2005), use of non-subject specific joint centre calculations and soft tissue artefacts (Reinschmidt, van den Bogert et al. 1997; Leardini, Chiari et al. 2005). We attempted to minimize these issues by using the same investigator (KD) for all marker placements, which decreased inter-participant variability. Furthermore, because participants had differing squat strategies, are results had high variability. Lastly, our sample size was not large enough to obtain good statistical power ($\beta < 0.6$ for all variables). In addition to the high variability in our results, this may account for the lack of statistical significance. Adding more subjects may potentially fix this. Analysis with G*Power software (version 3.1.0) (Faul, Erdfelder et al. 2007) was used to conduct a power analysis on our primary outcome data. The analysis determined that a sample size of 24 in each group was necessary to effectively test the research hypotheses ($\alpha \leq 0.05$, $\text{power} \geq 0.80$).

CONCLUSION

The key research questions that still remain are: is FAI a result of pain and joint damage such as labral tears and cartilage damage? Does it take years of slow joint degradation and changes to the lower body musculature of the FAD group to cause the observed changes in the symptomatic group? Do you need FAD to develop sFAI (can a control develop sFAI symptoms)? Or perhaps are some other factors are connected with FAI?

While the exact mechanism of FAI still requires further research, thus far it is clear that alpha angle is strongly associated with FAI, but there may be many other potential co-factors that are responsible for the development of symptoms. Our data suggests the squat biomechanics of asymptomatic FAD patients do not largely differ from the control group. The symptomatic FAI group reports smaller pelvic ROM, peak hip flexion angle, and squat depth compared to controls, which have been previously reported. The FAD group does not suffer from the same kinematic restrictions as the FAI group, and has no discernable pain, stiffness, or overall reduced hip function as demonstrated from the WOMAC and HOOS results. The sFAI group has significantly reduced hip function, more reported pain and stiffness compared to controls and FAD, which has been previously reported. Furthermore, the MVIC results suggest no muscle weaknesses were present in any group, which indicates that the musculature has not adapted in a way that causes muscle weakness in sFAI and FAD.

These results indicate that the mechanical impingement may not be the only factor restricting squat motion, but also soft tissue such as capsule and ligaments and labral, other factors such as pain, anatomical hip parameters such as femoral neck shaft angle, joint stiffness and potential neural muscular imbalances could also limit squat motion. Further investigation into these variables and if they have any influence on the biomechanics of the squat, and other motion tasks, is suggested. This may help develop a method for early diagnosis of the FAI, to prevent corrective surgery and arthritis, and understand the cause for symptoms.

Acknowledgements

The authors would like to thank Daniel Varin, Giulia Mantovani, and Matthew Kennedy for their contribution to data collection and processing. Also, thanks to Kyle Kemp, Gillian Parker, and Heather Belanger for their work in patient recruitment. This study has been partly funded by the Canadian Institutes of Health Research.

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ARTICLE 2

GAIT KINEMATIC AND KINETIC ANALYSIS OF ASYMPTOMATIC CAM FEMOROACETABULAR DEFORMITY PARTICIPANTS COMPARED TO SYMPTOMATIC FAI AND CONTROLS

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ABSTRACT

It is known that femoral head deformity and decreased concavity at the head/neck junction increases the likelihood of impingement between the femoral head and the acetabulum during certain movements. This condition is known as femoroacetabular impingement (FAI) and cartilage damage and hip pain are associated with it. Studies have shown that FAI results in decreased hip extension, adduction, and abduction during level walking, but it is unclear whether these deficiencies are due to the deformity or the additional joint damage. Three distinct groups were studied: asymptomatic femoroacetabular deformity (FAD), symptomatic FAI (sFAI), and matched controls (CON). The aim of the study consisted of comparing both asymptomatic FAD and symptomatic FAI to controls hip kinematics and kinetics during gait. The purpose was to test the isolated FAD deformity to see if participants have the same gait deviations as their symptomatic counterparts. It was hypothesized that sFAI and FAD groups would both have the same biomechanical differences when compared to the CON group. However, our results did not clearly find any statistically significant differences between any of the groups. One noticeable trend was the repeated findings from earlier studies in which the sFAI group had decreased peak hip extension and abduction angle, and total frontal pelvic ROM. It is believed that this result may be a gait adaptation based on the pain that sFAI participants endure. Unfortunately, the FAD group did not have gait patterns similar to either the CON or sFAI, making it unclear if the asymptomatic cam deformity has any gait adaptation effects.

KEY WORDS: femoroacetabular impingement, FAI, gait, level walking, hip

INTRODUCTION

Femoroacetabular impingement (FAI) is an idiopathic progressive anatomical hip disorder, most commonly found in young athletic males. It is characterized by an aspherical femoral head and alpha angle is the measurement used to assess the degree of asphericity known as cam deformity (Notzli, Wyss et al. 2002; Beck, Kalhor et al. 2005; Rakhra, Sheikh et al. 2009; Sutter, Dietrich et al. 2012). This will cause abnormal contact between the femoral head/neck and acetabular rim during movement and is responsible for causing hip pain and impinging one's range of motion. It can affect joint kinetics and kinematics during functional tasks, such as walking (Kennedy, Lamontagne et al. 2009; Hunt, Gunether et al. 2013; Rylander, Shu et al. 2013). Affected FAI joints share similarities to osteoarthritis (OA) and are believed to be linked to the development of OA symptoms later in life (Harris 1986; Ito, Minka et al. 2001; Ganz, Parvizi et al. 2003; Leunig and Ganz 2005).

While the impingement is typically attributed to large ROM activities such as squatting (Lamontagne, Kennedy et al. 2009) it has been found that in level walking FAI participants do have disturbed joint biomechanics (Kennedy, Lamontagne et al. 2009; Hunt, Gunether et al. 2013; Rylander, Shu et al. 2013). Kennedy found decreased peak hip extension and abduction angles, and a lesser total frontal pelvic and hip range of motion (ROM) in FAI subjects when compared to healthy controls. Hunt (2013) also found a decreased peak hip extension and abduction, in addition to decreased hip adduction. Rylander (2013) found significantly reduced hip internal rotation and hip sagittal plane ROM in FAI subjects during walking when compared with controls.

There is no definitive evidence whether these biomechanical variations in FAI are due to pain and soft tissue damage or mechanical impingement, and it is necessary to assess patients with asymptomatic cam femoroacetabular deformity (FAD) and symptomatic femoroacetabular impingement (sFAI) to help distinguish the effects of the cam deformity from the effects of the symptoms. No study has yet to look at the gait patterns of an asymptomatic FAD group. The cam deformity is located in the anterosuperior region of the femoral head/neck, presumably resulting from constant repetitive contact, which typically occurs during flexion and internal rotation (Leunig and Ganz 2005; Tannast, Kubiak-Langer et al. 2007) at the limits of hip ROM (Ito, Minka et al. 2001). However, recent research suggested that the observed ROM limitations when doing daily functional tasks may be due to soft tissue damage and muscle adaptations that cause apprehension and pain, and not directly related to the contact of the femoral head and acetabulum (Kennedy, Lamontagne et al. 2009). Other studies postulated that gait abnormalities are due to the cam deformity (Hunt, Gunether et al. 2013) since the walking task actually does reach the limits of an affected hips ROM. This study will address this issue by comparing the FAD group to symptomatic FAI and CON participants. Therefore comparative motion analysis is among three groups; sFAI participants who have the enlarged, aspherical femoral head, labral damage, and pain symptoms; asymptomatic FAD participants who have the bone deformity at the femoral head-neck junction but show no symptoms of pain or clinical signs, and a control group (CON) matched by age, gender, and BMI would show the effect of the cam deformity on joint motion and loading. The purpose of this study was to compare the kinematics and kinetics of the hip during level walk of the three distinct groups. It was hypothesized that the FAI group would have reduced peak extension, adduction and abduction

angle, as well as reduced frontal pelvic and hip total ROM as was found previously, when compared to CON. The FAD group would have similar biomechanics to the sFAI group and therefore similar deficiencies when compared to CON. This would be the result of the cam deformity's interaction with the acetabulum causing motion deficiencies.

MATERIALS AND METHODS

Participants

Fifty-one male participants were recruited to participate in the study, and distributed as follows: 17 CON, 18 FAD, and 16 sFAI. To determine if participants qualified for the study, computerized tomography (CT) scans were done and measured for alpha angle to determine CON or FAD status. Acetabular over coverage was also measured to ensure no participants had pincer FAI, another variation of FAI. Based on the literature an alpha angle value greater than 50.5° in the axial plane and greater than 60° in the radial plane is the standard cutoff used to diagnose FAI (Notzli, Wyss et al. 2002; Sutter, Dietrich et al. 2012; Sutter, Dietrich et al. 2012). Based on standard intra-reliability sources of error (Notzli, Wyss et al. 2002) for measuring alpha angle in imaging studies, a “grey zone” of $\pm 2.5^\circ$ of the axial and radial cutoffs was implemented. This helped ensure participants could be reliably determined to be part of either the FAD or CON group, otherwise they were excluded. Two participants fell into the grey zone and were excluded. One CON participant was excluded because force plate errors left their kinetic data unusable. These exclusions made the final numbers for participants at 14 for CON, 18 for FAD, and 16 for sFAI, as presented in Table 6.

The sFAI group was recruited through the Ottawa Hospital after they presented signs of positive impingement test and visible cam morphology on CT scans. This study was approved by the Ottawa Hospital Research Group and the University of Ottawa Health Sciences and Sciences Research Ethics Board. All participants signed informed written consent prior to participating.

Table 6 – Participant demographics, with the mean and standard deviation (SD).

Variable	CON	FAD	sFAI
Participants	14	18	16
Age (years)	32.6 (6.8)	31.2 (5.0)	38.8 (8.6)
Height (cm)	176.9 (6.9)	179.6 (4.9)	175.9 (6.2)
Weight (kg)	82.7 (12.5)	83.2 (10.5)	84.5 (16.0)
BMI	26.4 (3.4)	25.8 (2.8)	27.3 (4.6)
Affected Axial AA (deg)	41 (4.8)	58 (9.2)	56 (8.4)
Affected Radial AA (deg)	50 (2.4)	68 (7.8)	65 (7.8)

Protocol

Participants had a CT scan at the Ottawa Hospital. This was done in order to confirm their status as FAD or CON, and the results were used to calculate the alpha angle. The affected side for CON was the side with a smaller axial-radial combined alpha angle. The affected side for FAD was the side with a greater combined alpha angle. In case that both hips showed signs of FAD, the side with the larger deformity was chosen as the affected side.

Motion data was collected on the same day as the CT scan. Ten Vicon MX-13 motion capture cameras (Vicon, Oxford Metrics, Oxford UK) were used to capture trials, and collected data at a

200 HZ frequency. One Bertec force plate (FP4060, Bertec Corp., Columbus, OH, USA) and one Kistler force plate (9286BA, Kistler Instruments Corp, Winterhur, Swtz) collected ground reaction forces at a frequency of 1000 HZ (Beaulieu, Lamontagne et al. 2010). Participants put on a skin-tight suit and had a 45 retro-reflective full body marker set placed on anatomical landmarks, with necessary anthropometric measurements taken. The participants were instructed to use a self-selected walking pace (Crowinshield, Brand et al. 1978; Mockel, Perka et al. 2003; Bejek, Paroczai et al. 2006) looking straight ahead, from the same starting position at every trial. They also performed practice trials in order to become comfortable and capable of striking the force plates without altering their gait. A total of 5 good walking trials were collected and averaged for each participant. An example of a walking trial can be seen in Figure 5. The walking trials were time normalized from heel strike to heel strike.

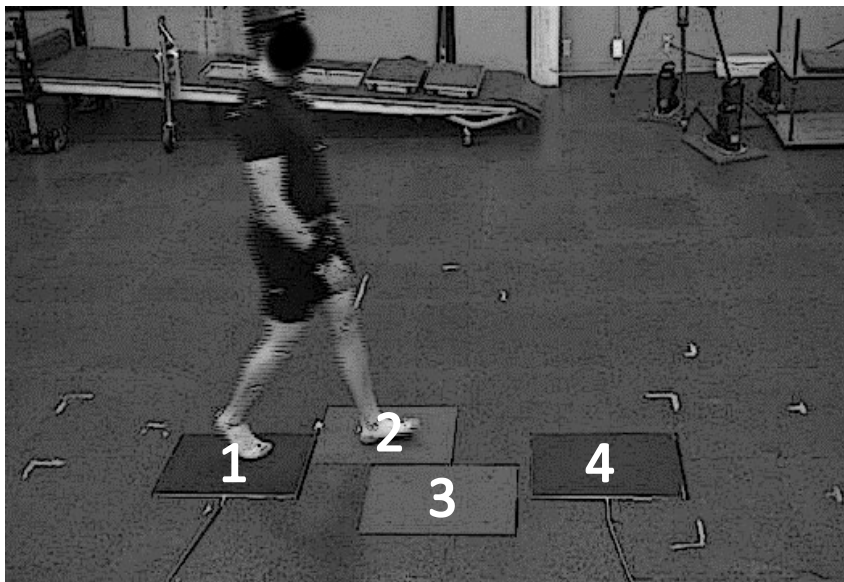


Figure 6 - Example of a participant performing a level walking trial. Force plates 1 and 4 are Kistler force plates, and force plates 2 and 3 are Bertec force plates.

Data Analysis

Force plate data were conditioned using a second order dual- low-pass Butterworth filter (8Hz) while reflective marker trajectories were filtered with a 15 MSE woltring filter (Woltring 1986). Kinematic and kinetic data for the leg of interest was computed using a modified plug-in-gait model (Beaulieu, Lamontagne et al. 2010) in Body Builder software (version 3.6.1, Vicon, Oxford, UK). Custom MATLAB software (MATLAB, The MathWorks, Inc., Natick, Massachusetts, USA) was used to extract the kinematic and kinetic parameters and average the trials. Dependant variables were: Total frontal and sagittal pelvic ROM, total frontal and sagittal hip ROM, peak hip flexion and extension, peak hip adduction and abduction, peak sagittal and frontal hip moments, and maximum and minimum hip powers. For each dependent variable, a one-way analysis of variance (ANOVA) was used to test for significant differences between groups. A Bonferroni correction adjusted the alpha value to 0.025 since two dependant planes of motion were analyzed. Coefficient of variance (CV) was calculated individually for each variable to assess the total variability, using the following equation (Giroux and Lamontagne 1992; Benoit, Lamontagne et al. 2003):

$$CV = \frac{\sqrt{\frac{\sum(\sigma^2)}{n}}}{\sqrt{\frac{\sum x^2}{n}}} \quad (2)$$

Where σ is the standard deviation at each data point, and x is the group mean averaged at each data point, and n is the total sample size. Statistical analysis was conducted using SPSS version 19 software (IBM Corporation, Armonk, New York, USA).

RESULTS

Kinematics

Group means and standard deviations of kinematic hip variables tested are present in Table 7. There was no difference in walking speed between groups. The frontal pelvic ROM is presented in Figure 6. There were no differences in sagittal pelvic ROM ($p = 0.442$) and the CON group had slightly larger frontal pelvic ROM than FAD and sFAI but it was not significant ($p = 0.451$). Hip flexion and extension angles are presented in Figure 7. The CON and FAD groups achieved greater peak extension than the sFAI, but it was not significant ($p = 0.433$), and there were no significant differences in hip flexion ($p = 0.76$) or total sagittal hip ROM ($p = 0.356$). Hip adduction and abduction are presented in Figure 8. The CON and FAD achieved greater hip abduction than sFAI but it was no significant ($p = 0.031$), nor was adduction ($p = 0.150$) or total frontal hip ROM ($p = 0.178$). A Coefficient of variability analysis was performed to assess the between group variability for each variable, as summarized in Table 9.

Table 7 – Mean values (SD) for key level walking kinematic variables for CON, FAD, and sFAI.

Group/Variable	CON	FAD	sFAI	p-value
	Mean (SD)	Mean (SD)	Mean (SD)	
Sagittal Pelvic ROM (deg)	3.0 (0.9)	3.3 (0.8)	3.4 (0.8)	0.442
Frontal Pelvic ROM (deg)	11.3 (2.5)	10.1 (2.8)	10.2 (2.9)	0.451
Sagittal Hip ROM (deg)	49.6 (5.2)	48.6(5.6)	46.6 (5.8)	0.356
Peak Hip Extension Angle (deg)	-16.9 (2.6)	-17.3 (4.9)	-14.7 (8.6)	0.433
Peak Hip Flexion Angle (deg)	32.4 (4.2)	31.2 (4.1)	32.1 (5.6)	0.765
Frontal Hip ROM (deg)	15.5 (3.2)	15.2 (3.6)	13.5 (2.7)	0.178

Peak Hip abduction Angle (deg)	-7.3 (2.6)	-5.0 (2.4)	-4.3 (4.1)	0.031
Peak Hip adduction Angle (deg)	8.1 (2.6)	10.3 (3.5)	9.2 (2.8)	0.150

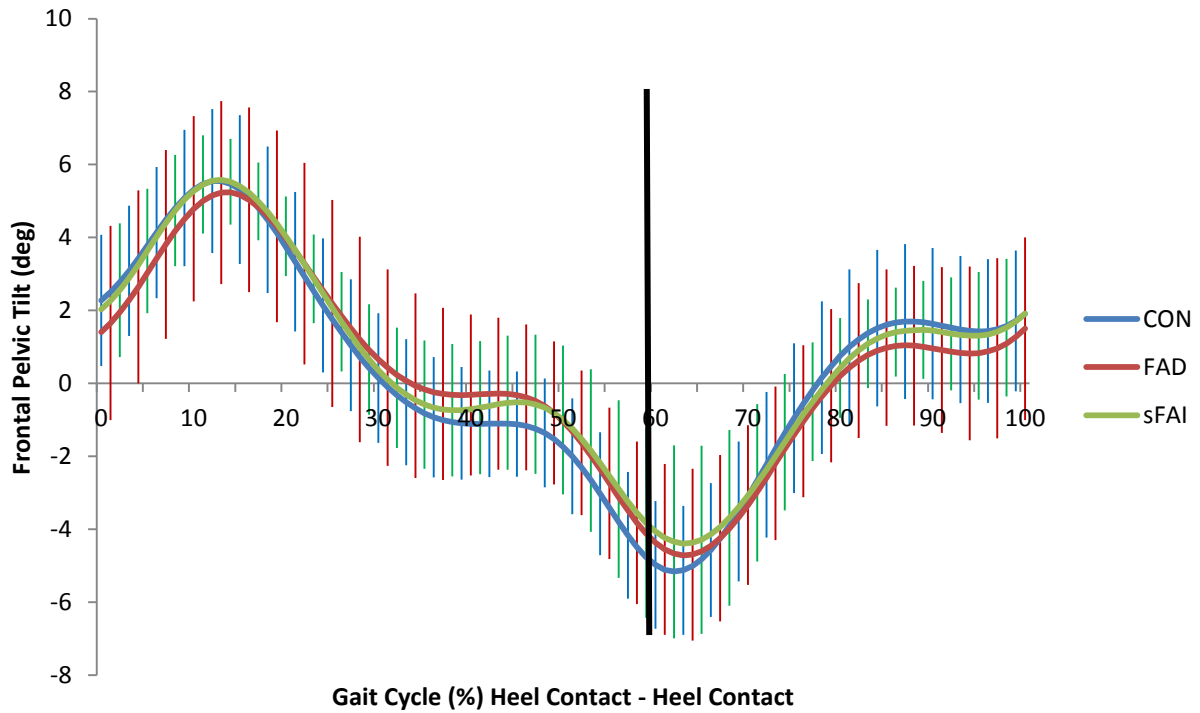


Figure 7 - Mean (\pm standard deviation) of frontal pelvic tilt angles (deg) of the FAD, sFAI and control groups during level gait. The black vertical line represents toe-off, which occurs at approximately 60% of the gait cycle.

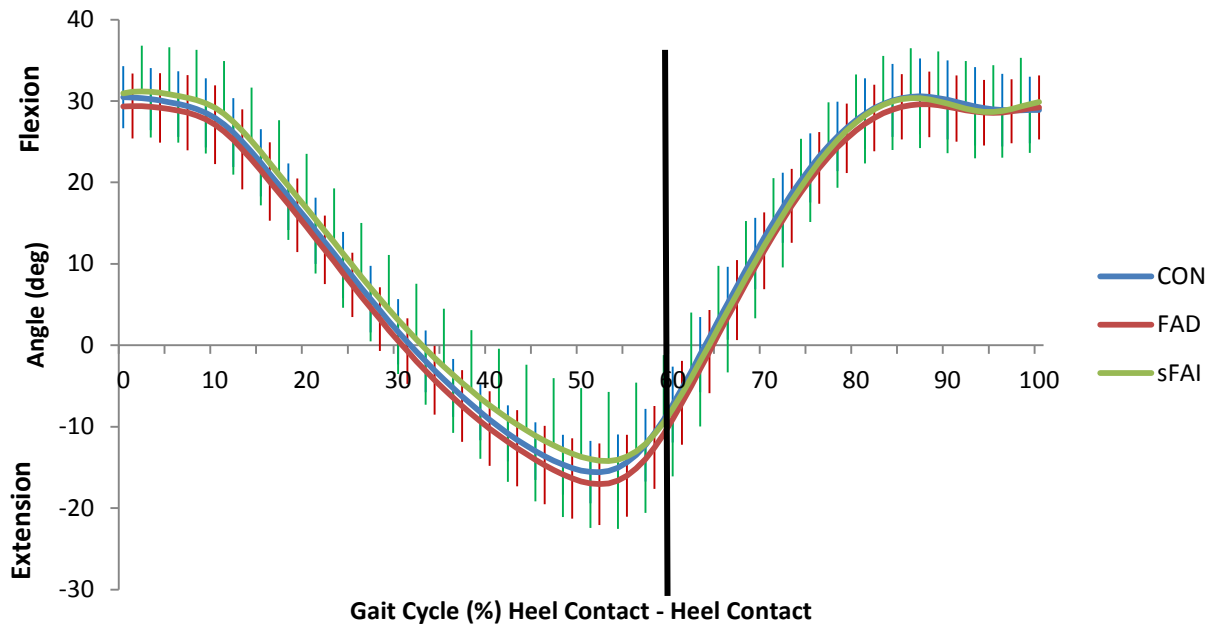


Figure 8 - Mean (\pm standard deviation) of sagittal hip angles (deg) of the FAD, sFAI and control groups during level gait. The black vertical line represents toe-off, which occurs at approximately 60% of the gait cycle.



Figure 9 - Mean (\pm standard deviation) of frontal hip angles (deg) of the FAD, sFAI and control groups during level gait. The black vertical line represents toe-off, which occurs at approximately 60% of the gait cycle.

Kinetics

Group means and standard deviations of kinetic hip variables tested are present in Table 8. Hip flexion moment and hip adduction moment, and hip powers normalised to gait are presented in Figures 9, 10 and 11. There were no significant differences in peak hip flexion, extension, abduction or adduction moment ($p = 0.284, 0.645, 0.317, 0.531$). There were no differences in maximum or minimum hip powers ($p = 0.125$ and $p = 0.108$ respectively). A Coefficient of variability analysis was performed to assess the between group variability for each variable, as summarized in Table 9.

Table 8 – Mean values (SD) for kinetic dependant variables during level walking, for the CON, FAD, and sFAI groups.

Group/Variable	CON Mean (SD)	FAD Mean (SD)	sFAI Mean (SD)	p-value
Peak Hip Flexion Moment (Nm/Kg)	1.23 (0.2)	1.15 (0.4)	1.04 (0.4)	0.284
Peak Hip Extension Moment (Nm/Kg)	-0.65 (0.1)	-0.62 (0.1)	-0.59 (0.2)	0.645
Peak Hip Adduction Moment (Nm/Kg)	-0.70 (0.1)	-0.72 (0.2)	-0.64 (0.2)	0.317
Peak Hip Abduction Moment (Nm/Kg)	0.26 (0.09)	0.26 (0.06)	0.22 (0.1)	0.531
Max Hip Power (W/Kg)	1.34 (0.4)	1.44 (0.4)	1.17 (0.4)	0.125
Min Hip Power (W/Kg)	-0.92 (0.3)	-0.85 (0.3)	-0.70 (0.4)	0.108

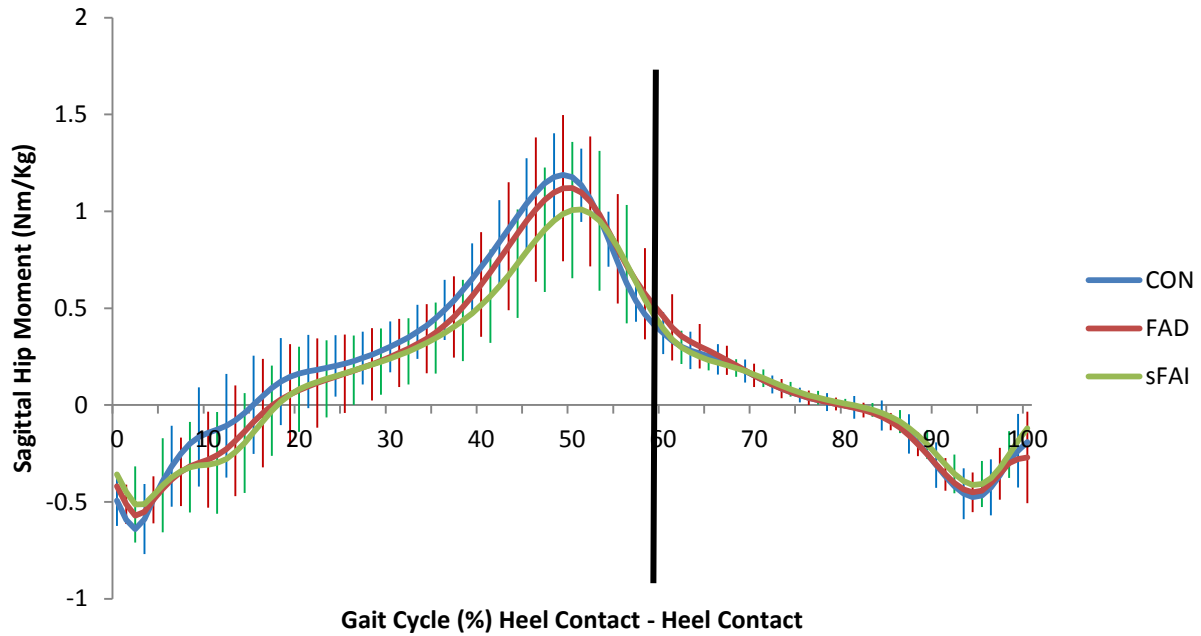


Figure 10 - Mean (\pm standard deviation) of sagittal hip moments (Nm/Kg) of the FAD, sFAI and control groups during level gait. The black vertical line represents toe-off, which occurs at approximately 60% of the gait cycle.

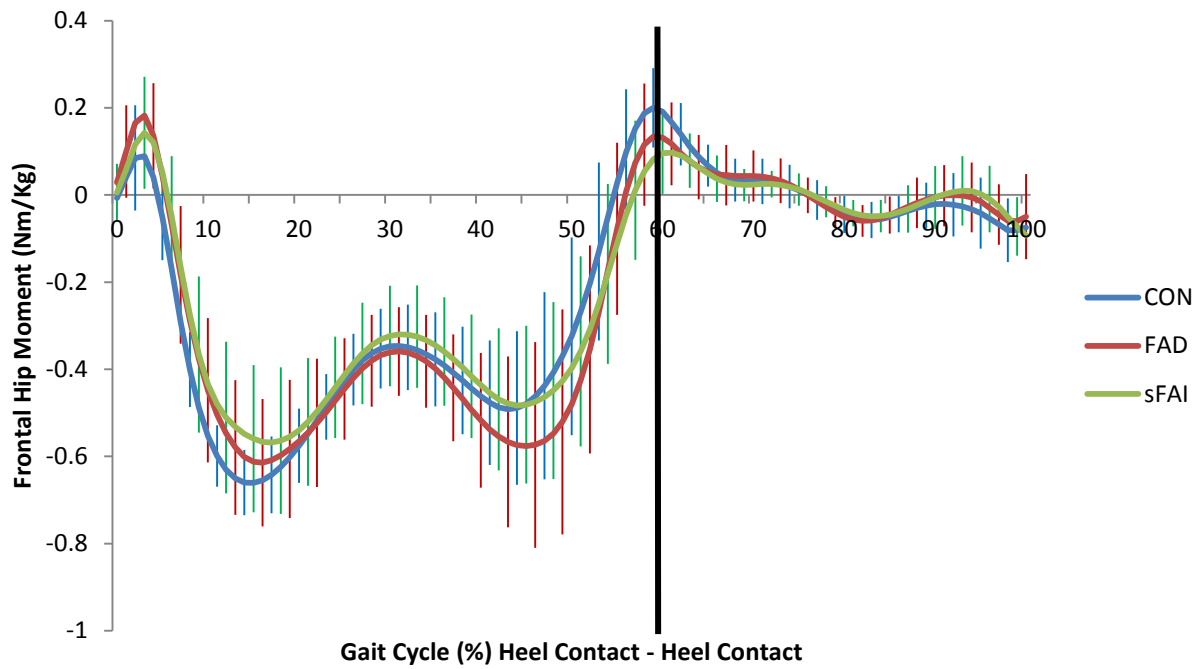


Figure 11 - Mean (\pm standard deviation) of frontal hip moments (Nm/Kg) of the FAD, sFAI and control groups during level gait. The black vertical line represents toe-off, which occurs at approximately 60% of the gait cycle.

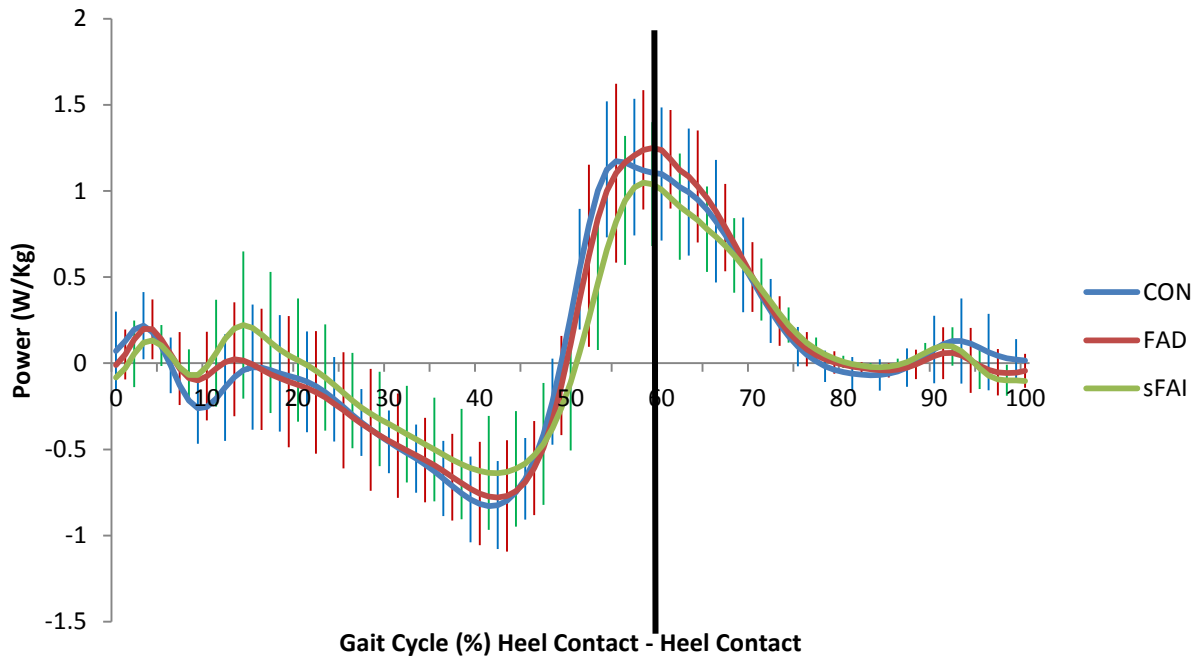


Figure 12 - Mean (\pm standard deviation) of hip powers (W/Kg) of the FAD, sFAI and control groups during level gait. The black vertical line represents toe-off, which occurs at approximately 60% of the gait cycle.

Table 9 – Coefficient of variation of all analyzed variables, for all three groups (CON, FAD, sFAI).

Coefficient of Variation	CON	FAD	sFAI
Pelvis Frontal Angle (deg)	0.63	0.88	0.65
Hip Sagittal Angle (deg)	0.20	0.22	0.34
Hip Frontal Angle (deg)	0.60	0.66	0.62
Hip Sagittal Moment (Nm/Kg)	0.33	0.43	0.46
Hip Frontal Moment (Nm/Kg)	0.33	0.40	0.42
Hip Power (W/Kg)	0.49	0.52	0.61

DISCUSSION

The primary objective of this study was to examine the effects of cam deformity and FAI by analyzing lower-extremity joint kinematics and kinetics of FAD, sFAI, and CON participants during level walking at a self-selected pace. Based on previous studies (Kennedy, Lamontagne et al. 2009; Hunt, Gunether et al. 2013; Rylander, Shu et al. 2013) it was hypothesized that both the sFAI and FAD group would achieve lesser peak extension angle, greater peak abduction angle, and a larger frontal and sagittal hip ROM than the CON group. Our results did not support our hypothesis. All variables had no significant differences in any of the kinematic or kinetic variables among groups.

However, in lieu of statistical significance for the kinetic and kinematic results, we did observe some interesting trends that warrant discussion. The sFAI and FAD had a strong trend of decreased peak hip abduction after toe off. The FAD also had a greater adduction angle, and therefore a greater total frontal hip ROM than the sFAI, indicating that while they experienced an unexpected reduction in peak hip abduction, their compensation of larger adduction and frontal hip ROM resulted in a comparable frontal hip kinematics to the CON group. The sFAI group however experienced a trend of decreased peak hip abduction, and also a weak trend of decreased frontal hip ROM and hip adduction, indicating a lacking ability to have a full frontal hip ROM. This may be due to the reported higher levels of hip pain the sFAI group experiences. If the cam deformity is not responsible for this gait alteration, pain and neuromuscular adaptations can cause this adapted gait response. It has been found that induced pain of the hip abductors via intramuscular saline injection can cause decreased hip abduction moment

during walking (Henriksen, Aaboe et al. 2009), and may explain the observation of reduced hip abduction angle in our sFAI group.

The sFAI and CON groups closely matched the findings in the previous study on level walking (Kennedy, Lamontagne et al. 2009; Hunt, Gunether et al. 2013) despite the lack of significance. The total frontal pelvic ROM was slightly greater for the CON than sFAI, however, the Kennedy (2009) study did find larger differences at the both the beginning of stance phase and directly before toe off, but our results only found greater difference at toe off for the CON group compared to sFAI. We similarly found peak extension angle at the end of the stance phase was greater for the CON group than the sFAI group, which was also observed in both Kennedy (2009) and Hunt (2013). We also found greater overall sagittal ROM for the entire cycle, but this is likely a function of the greater peak hip extension. Finally, the most noteworthy trend was the greater peak hip abduction angle directly after toe off in the CON group, which resulted in a greater over frontal hip ROM for the CON group. Both studies noted this difference, but Hunt (2013) also found an increased peak adduction angle in the CON group.

Since the sFAI and CON groups had results that were repeatable from previous results, a surprising finding is the lack of consistency in the FAD group to conform to either a sFAI or CON pattern. The FAD group had greater peak hip extension angle, and a greater adduction angle, but not a greater abduction angle than sFAI. We found the CON group had greater abduction compared to sFAI and FAD, and the FAD group had larger adduction angles than the sFAI group. Also, the frontal pelvic ROM and pelvic tilt of the FAD group were not appreciably any different than the sFAI, whereas the CON group was. Given the lack of statistical significance and the fact

the FAD group did not entirely match the gait patterns of either the sFAI or the CON, we are therefore unable to determine the extent of the role that asymptomatic cam deformity has in altered gait.

There is a strong argument for the idea that kinematic limitations observed in sFAI during gait are not the result of the cam deformity, since maximum ROM is not achieved during level walking. Any subsequent biomechanical differences is suggested to result from from pain, soft tissue damage, or neuromuscular adaptation. In fact, the authors of one of the previous FAI gait studies acknowledge this (Kennedy, Lamontagne et al. 2009). However, authors of the another FAI gait study (Hunt, Gunether et al. 2013) argued that there may be some impingement because hip extension and adduction approach their maximum ROM during level walking. Despite these contradicting ideas, by studying the FAD group the goal was to confirm or refute this argument, and see if the cam deformity had influence on gait parameters. Unfortunately the results were not conclusive. However, in light of the fact that our sFAI and CON were not significantly different from each other as found in several previous studies, whereas squatting tasks and physical examinations that had a full ROM were able to achieve significant differences and strong trends (Leunig and Ganz 2005; Tannast, Kubiak-Langer et al. 2007; Lamontagne, Kennedy et al. 2009; Lamontagne, Brisson et al. 2011), it appears that walking may not be sensitive enough to reliably find deficiencies in sFAI or FAD.

It is unclear why our results differed from previous findings, particularly why we lacked statistical significance. We did observe relatively low power ($\beta < 0.657$) for all the observed variables and our small sample size may be a factor. Another possibility is that other studies

had sFAI groups that experienced more pain, and in general had more symptoms than ours. Given the lack of guidelines that defines FAI, it is certainly possible that the FAI group of one study could be different from the FAI group of another study. Ideally all studies would have the same criteria, such as unilateral cam FAI only (no pincer FAI), with the same cutoffs for alpha angle (both axial and radial) and medical images to assess the level of cartilage and labral damage. However, this is not the case. In fact, the Hunt (2013) study had 6/28 subjects with a mixed pincer/cam FAI. The Kennedy study (2009) did use unilateral cam FAI, but they only assessed the axial alpha angle. This is in contrast to our study, which assessed both axial and radial angle, but found that the majority of our sFAI participants (15/16) had a bilateral cam deformity, despite only presenting with symptoms on one side. If the FAI groups of other studies did experience more pain or had more soft tissue damage to the cartilage and labrum, over time more pain will likely result in more neuromuscular adaptations and a greater altered gait patterns than a low pain FAI group. However it would be extremely difficult to compare since no study used exactly the same pain assessment metric. Additionally, we had an uncharacteristically large CV for all the kinematic and kinetic variables of each group. This large variation in our gait parameters may explain why our results did not achieve statistical significance.

CONCLUSION

It was found that there were no statistically significant differences in kinematic or kinetic variables between the sFAI, FAD, and CON groups. There was an observed trend that sFAI had

reduced frontal hip ROM and peak abduction angle, results that were also previously reported in other studies (Kennedy, Lamontagne et al. 2009; Hunt, Gunether et al. 2013). Meanwhile, the CON group had typical gait patterns for healthy participants. Since there is strong speculation that the cam deformity is not responsible for gait alterations in symptomatic FAI, the lack of conclusive findings in the FAD may be interpreted as further evidence that the cam deformity is not the underlying contributor to gait alterations in the asymptomatic group either. If the cam deformity was responsible for gait alterations, the FAD would more have more clearly similar biomechanical gait patterns with the sFAI group. It is clear that the sFAI uses a different gait strategy, which may be the result of joint damage and pain, and/or neuromuscular adaptations. Further analysis into muscle activation in combination with all these results may yield further insight, and is currently underway.

Acknowledgements

The authors would like to thank Daniel Varin, Giulia Mantovani, and Matthew Kennedy for their contribution to data collection and processing. Also, thanks to Kyle Kemp, Gillian Parks, and Heather Belanger for their work in patient recruitment. This study has been partly funded by the Canadian Institute of health Research.

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GENERAL DISCUSSION

It was predicted the kinematic deficiencies found in the sFAI group from previous studies would also be present in the FAD group based on the diagnosed cam deformity. However, we found no statistical significance in any of the squat or walking kinematic or kinetic variables; although a minor decreased peak hip abduction angle during level walking for the sFAI group was observed. Previous studies on level walking in sFAI (Kennedy, Lamontagne et al. 2009; Hunt, Gunether et al. 2013; Rylander, Shu et al. 2013) also observed similar findings. This outcome may be a neuromuscular adaptation due to chronic pain. It has been found that hip abductor pain (induced by hypertonic saline solution in the gluteus medius) can lead to reductions in hip abduction moment (Henriksen, Aaboe et al. 2009) and therefore pain experienced by the sFAI may explain the reductions in hip abduction angle.

For the squat task we did observe some interesting differences. First, the CON group and FAD group demonstrated an ability to achieve greater squat depths, hip and total pelvic ROM when compared to the sFAI group. In support, previous work by Lamontagne et al (2009) found that the sFAI had significantly less squat depth and a decreased pelvic ROM than CON. Considering the similar hip and knee flexion angles and pelvic ROM between the FAD and CON group, it may suggest that the FAD group had no major physical restriction due to bone deformity to prevent maximal squat depth. The reduced squat depth in the sFAI group relative to the FAD indicated that the symptoms of FAI, such as pain and joint damage could be associated with reduced squat depth.

It was also found that the sFAI had significant reductions in external rotation and internal rotation during physical examinations. There was a strong trend that showed a reduced hip flexion angle as well. The sFAI results closely matched previous literature, which found decreased internal rotation and hip flexion compared to controls (Tannast, Kubiak-Langer et al. 2007). With regards to external rotation and hip flexion, the FAD group behaved the same as the CON group and had no statistically significant deficiencies. Interestingly, the FAD group did have a strong trend indicating reductions in internal rotation angle compared to CON during physical exam. This indicates the internal rotation test may have the capacity to predict the presence of cam deformity compared to controls. Since the internal rotation physical exam was tested at a true maximum ROM, this may explain why only this parameter found restrictions in the FAD. The act of having the thigh internally rotated to its limit saw the cam deformity actually cause a physical jamming with the acetabulum, given its location at the anterosuperior aspect of the femoral head.

Overall the sFAI had decreased moment of force compared to FAD and CON for the hip muscle groups, and the CON and FAD groups were similar except for an increased hip extensor moment of force in the FAD compared to CON. However, none of the MVIC moments of force results were significant. Essentially, the FAD subjects have normal isometric hip strength as compared to healthy control. It is possible that absence of pain might be an important element in the ability to produce higher moments of force compared to the actual bone deformity, thus explaining the results of decreased moments in the sFAI group compared to FAD, but further study is needed to truly understand the effect FAI has on muscular strength. EMG analysis and

cross-sectional area studies of the muscles will be beneficial to help understand the relationship.

WOMAC and HOOS assessments clearly demonstrated the symptoms of sFAI, as that group reported significantly higher hip pain, decreased quality of life, decreased sport and recreation participation, greater stiffness, and overall less hip biomechanical function than both the FAD and CON. However, the FAD was no different than the CON group in terms of qualitative assessment. Since pain is unique only to the sFAI group, this is a possible explanation for most of the motion and physical exam limitations. Pain is known to cause motion limitations (Henriksen, Aaboe et al. 2009). However, it is important to re-iterate the pain aspect of sFAI was already a well-known feature, and is not a new finding. The purpose of the qualitative assessment was to assess the function of FAD, which was found to be comparable to controls.

The results from our study indicate that cam deformity would not be the only factor responsible for biomechanical variations; however these findings do not exclude cam deformity as a cause for developing symptoms, and it just indicates it is less likely the primary cause for motion deficiencies. Large cam deformity (as measured with alpha angle) has been proposed as a mechanism for development of acetabular labral-condral damage in patients with hip pain (Beaule, O'Neill et al. 2009). Acetabular articular cartilage damage in sFAI subjects is associated with larger alpha angles (Beaule, Hynes et al. 2012), as is increased acetabular bone density in both the FAD and sFAI group (15-34% higher and 14-38% higher, respectively) in the same region of the acetabulum where the cam deformity contacts (Speirs, Beaule et al. 2013). FAI subjects who undergo corrective surgery often require chondroplasty for the acetabular

cartilage damage and labral repair (debridement) (Beaule, Zaragoza et al. 2005; Beaule, Hynes et al. 2012). For example, in the 2005 Beaule study, all but one subject had labral repair, and in the 2012 Beaule study all subjects had labral tears that required repair. In our study all sFAI participants required labral repair and chondroplasty. However, no study to date has been done to see what percentage and rate the FAD population develop such damage. Since this type of joint damage is associated with FAI correction, further investigation into the prevalence rate of FAD subjects who develop labral tears would be beneficial. Cross-sectional studies are not effective at finding the relationship between asymptomatic FAD and symptomatic FAI. Longitudinal studies that investigate the prevalence and rate at which FAD develop labral, chondral and cartilage damage, and the association with alpha angle would be necessary to conclude the role that cam deformity has as a precursor to development of symptoms and future soft tissue damage in FAI subjects.

It is not fully clear when the onset of FAI symptoms begins, and what the etiology of the condition is. Much of the research focuses on alpha angle as the main measurement for assessing FAI (Notzli, Wyss et al. 2002; Beaule, Zaragoza et al. 2005; Tannast, Siebenrock et al. 2007; Leunig, Beaule et al. 2009; Rakhra, Sheikh et al. 2009; Jung, Restrepo et al. 2011; Sutter, Dietrich et al. 2012). However, it is possible the alpha angle is not totally effective in distinguishing asymptomatic FAI from symptomatic FAI, and other co-factors may be implicated in sFAI. If alpha angle is not effective in classifying FAI, then other potential confounding hip deformity factors, such as femoral neck-shaft angle, femoral head-neck offset, femoral and acetabular versions may be new variables for establishing a better FAD group (Tannast, Siebenrock et al. 2007). A recent study using the same current classification methods as our

study, observed that FAD have fairly normal femoral and acetabular versions when compared to controls (Ng, Lamontagne et al. 2013). However, the sFAI group had a significantly decreased femoral neck shaft angle and also notably reduced femoral head-neck offsets. This finding does not discard the notion of the cam deformity a proposed mechanism for development of symptoms, rather it indicates that alpha angle may not be the only consideration of potential mechanical impingement and biomechanical deficiencies, and other variables should be considered just as strongly. Further research is needed to see if femoral neck shaft angle and femoral head offset contribute to motion deficiencies, and whether they are implicated in early stage FAI. While this is just speculation, it is important to thoroughly investigate these variables to see if there are any biomechanical effects in level walking and other tasks. The goal is develop a more comprehensive understanding of early stage FAI and potential early diagnosis, which may prevent the need for corrective surgery and development of arthritis.

The strength of this thesis was doing comprehensive biomechanical analysis on FAD, a group that has never been studied before. There is much speculation in the literature whether the cam deformity is the cause of the impingement, or if all the combined joint damage in addition to the cam deformity is what defines FAI. The major finding in this thesis is that in general the FAD has similar biomechanical patterns to the CON group, and has none of the significant limitations that are found in the sFAI group. This suggests that the cam deformity, and large alpha angles as we defined our FAD group, is not responsible for any biomechanical deficiency that has been observed in the sFAI group previously or in this study. Evidence suggests the sFAI kinematic differences might be due to pain, joint and soft tissue damage. Several questions still need to be answered about the etiology of the condition. In order to do

this, a longitudinal study is required to follow FAD and CON patients over time and see the rate of development for symptoms, and whether they are isolated to the FAD group only.

CONCLUSION

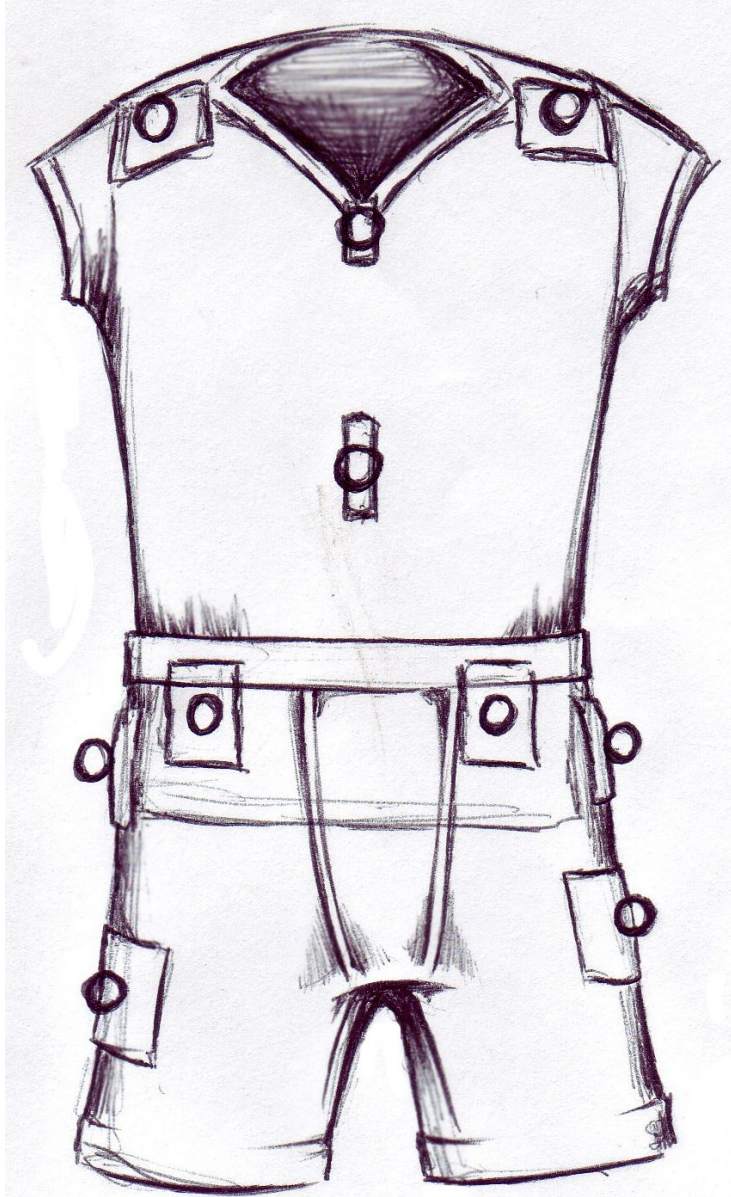
While the exact mechanism of FAI still requires further research, thus far it is clear that alpha angle is strongly associated with FAI, but there may be many other potential co-factors that are responsible for the development of symptoms. If the cam deformity is the cause for further joint damage, it will not cause any abnormalities or limitations on its own, without such joint damage. Our data suggests the squat and walking biomechanics of asymptomatic FAI patients do not largely differ from the control group, and there are no gait alterations or squat deficiencies in the FAD group. This indicates that the mechanical impingement may not be restricting during squats, walking or full ROM physical exams, but rather it is an issue of underlying soft tissue damage such as cartilage and labral lesions, pain, hip geometric co-factors, joint stiffness and potential neural muscular imbalances. Further analysis into potential geometric hip parameter co-factors may yield further insight into the etiology and pathomechanics of FAI.

The biomechanical effects of the FAI deformity in other tasks, as well as the potential influences of muscle co-activation is suggested as another avenue of study. This may help develop a method for early diagnosis of the FAI, to prevent corrective surgery and arthritis, and understand the cause for symptoms.

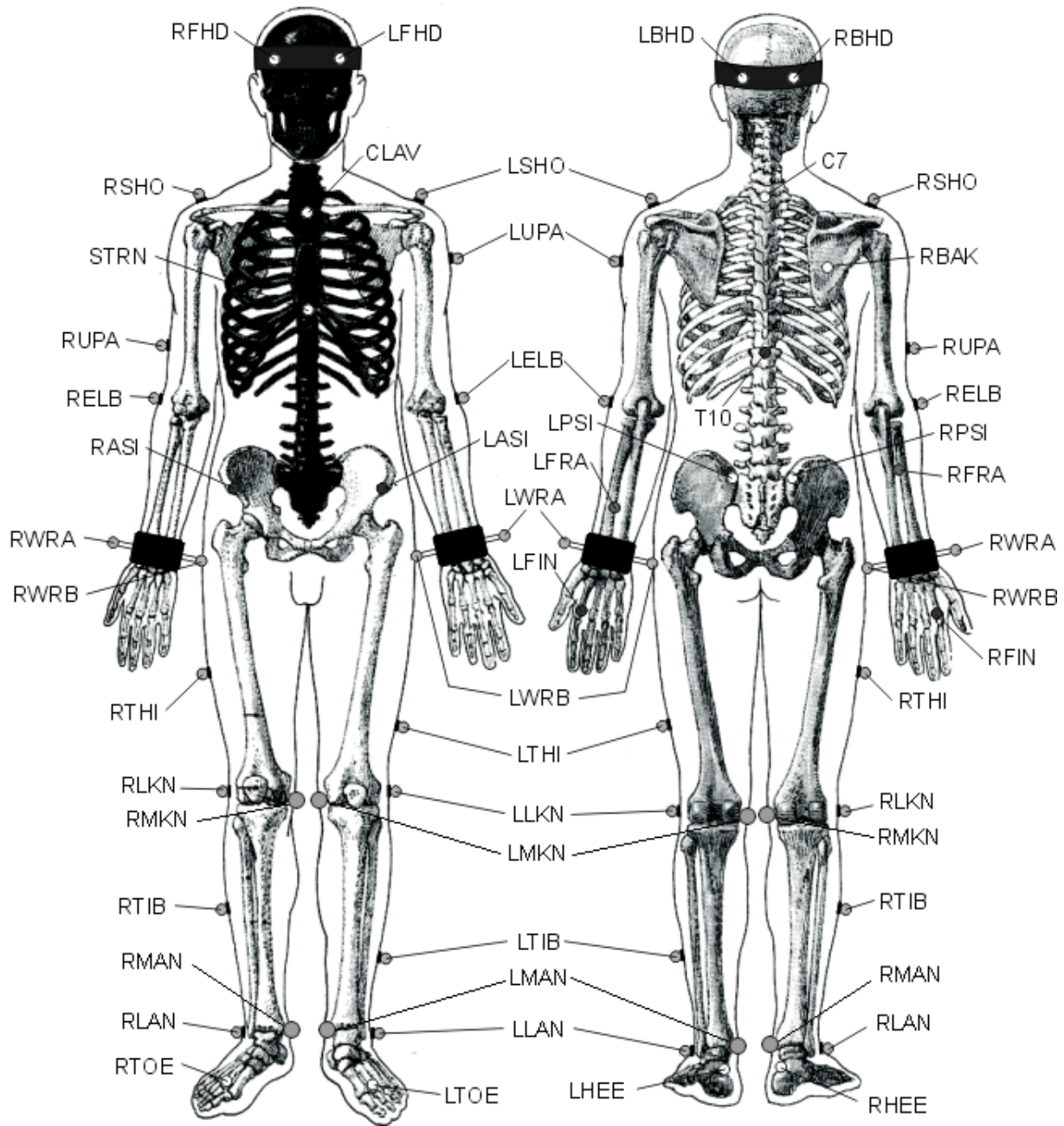
Appendix

Appendix A - List of pre-test anthropomorphic measures clinical examination results.

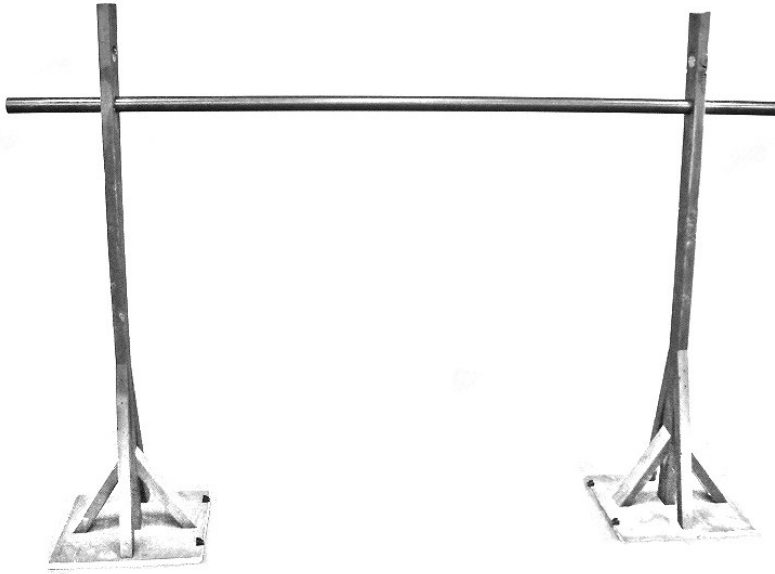
Measurement (units)	Description of measurement
Height (mm)	Participants height
Mass (kg)	Participants weight
Leg length (mm)	Left and Right leg length are measured, from ASIS marker to lateral malleolus on the ankle
Knee height (mm)	Distance from lateral epicondyle of the femoral to the floor
Ankle width (mm)	Distance between medial and lateral malleolus
Knee width (mm)	Distance between the lateral and medial epicondyle of the femur
Flexibility (cm)	Three Sit and Reach flexibility tests are performed
Leg dominance	Participants dominant leg
Leg raise angle (°)	Participants lays flat on the medical bench, keeping the pelvis straight while a straight leg raise is performed
Internal Rotation Angle (°)	Participant lays flat on the medical bench, keeping the pelvis straight, hip bent at 90° flexion, with knee bent at 90° flexion, while the maximum internal rotation angle is measured using a goniometer
External Rotation Angle (°)	Participant lays flat on the medical bench, keeping the pelvis straight, hip bent at 90° flexion, with knee bent at 90° flexion, while the maximum external rotation angle is measured using a goniometer
Hip Flexion Angle (°)	Participant lays flat on the medical bench, keeping the pelvis straight, as the maximum hip flexion angle is measured using a goniometer



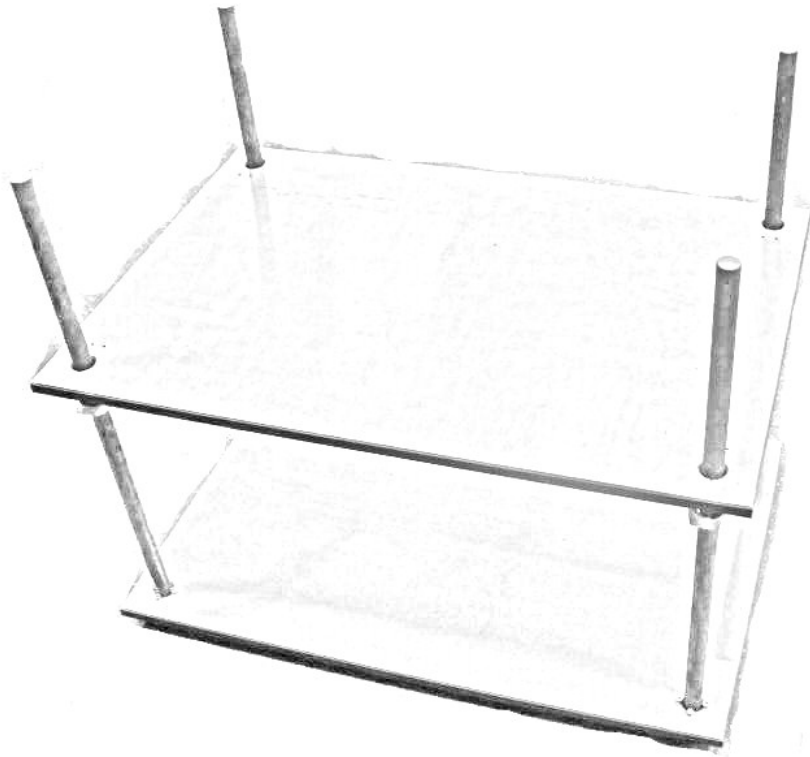
Appendix B – Lyrca suit with marker placements.



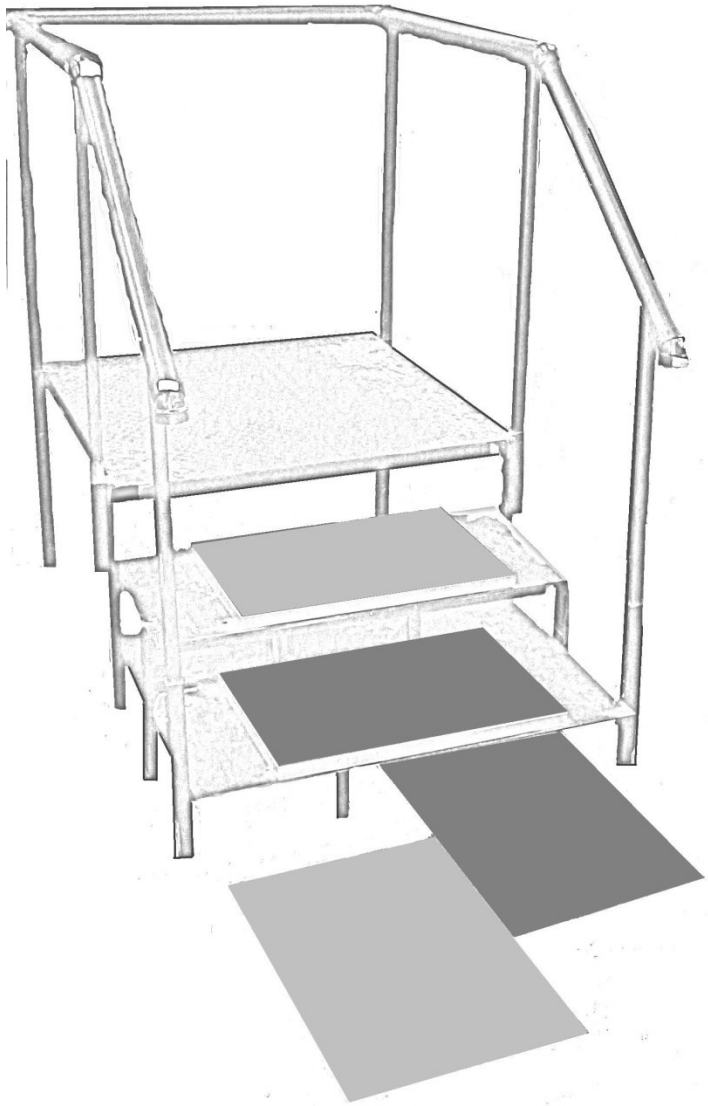
Appendix C – UOMAM marker placement model.



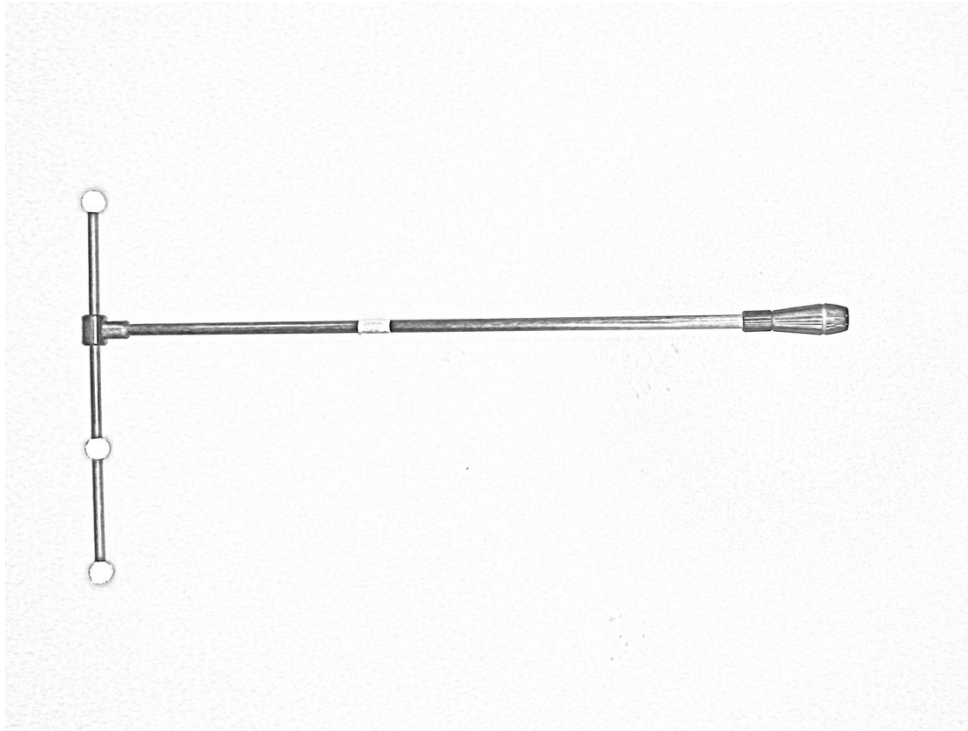
Appendix D – Dynamic ROM support bar.



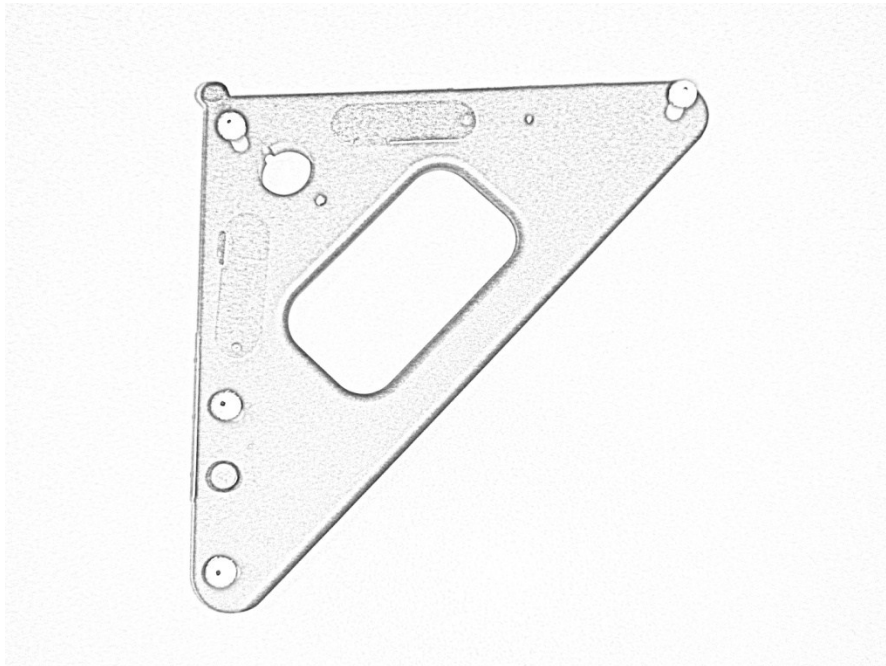
Appendix E – Height adjustable bench used in sitting/standing and squatting tasks.



Appendix F – Stairs rig with Kistler 9286AA and Kistler 9286A force plates on the steps. Bertec force plates are also shown.



Appendix G – T-shaped wand (240mm) used for camera calibration.



Appendix H – L-shaped frame (ErgoCal 14mm) used to set system origin.

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