BIOMECHANICS DURING CROSS-BODY LUNGING IN INDIVIDUALS WITH AND WITHOUT SYMPTOMATIC FEMOROACETABULAR IMPINGEMENT

by

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Abstract

Introduction:

Femoroacetabular impingement (FAI) is a patho-mechanical hip condition that involves abnormal contact between the femoral head/neck and the pelvis acetabulum. This abnormal contact can lead to impingement and restrictions in hip motion, particular in end-range hip flexion, adduction and/or internal rotation. Most of the biomechanical research to date has involved the symptomatic population (sFAI), where motion analysis was used to quantify differences in movement performance compared to healthy populations. However, the study of asymptomatic FAI (aFAI) is also important due to its high prevalence in the general population. The prevalence of FAI is also high in the athletic population; however there is a lack of studies that have analyzed a sport-specific movement. One such movement is the lunge, and because of the multidirectional nature of many sports, the 45˚ cross-body lunge was specifically chosen to be biomechanically analyzed.

Purpose:

The purpose of this thesis was to compare trunk and lower limb biomechanics during the 45˚ cross-body lunge between sFAI, aFAI and healthy control populations.

Methods:

33 total participants were recruited: 9 sFAI, 13 aFAI and 11 healthy individuals. In a single session, these participants were asked to perform the 45˚ cross-body lunge. Trunk, pelvis, hip, knee and ankle kinematics, as well as hip, knee and ankle kinetics and vertical ground reaction forces were examined.

Results:

Overall, there were very few statistically significant between-group differences in 45˚ cross-body lunge performance. Prior to outlier removal, though, the sFAI group exhibited a larger pelvis sagittal plane excursion during the entire movement than the aFAI group (p=0.046). After outlier removal, this difference was no longer statistically significant. As for knee sagittal moment net impulse, the only statistically significant difference became evident after outlier removal, where the aFAI group exhibited a larger knee sagittal moment net impulse than the control group (p=0.016).

Conclusions:

The results of our study generally show that sFAI, aFAI and healthy control populations perform the 45˚ cross-body lunge similarly. However, future research should aim to better understand pelvis and knee biomechanics during sporting activities like the lunge, as these parameters may have important implications in rehabilitation and sport performance.

Lay Summary

Femoroacetabular impingement (FAI) is a hip condition involving abnormal contact between the thigh bone and hip bone that has recently been termed a potential risk factor for hip osteoarthritis. Despite the high prevalence of FAI in the general and athletic populations, there is a lack of research analyzing how individuals with FAI perform common movements. To date, the lunge has not been examined in the literature. Our findings generally show that there are minimal differences in cross-body lunge performance between individuals with and without FAI. However, participants with FAI and pain seemed to show differences in pelvis kinematics compared to participants with FAI and no pain. Also, individuals with FAI and no pain showed increased loading at the knee compared to healthy participants. Despite similarities in lunge performance between FAI and non-FAI populations, pelvis and knee movements are potentially important variables to consider during FAI rehabilitation and training.

Preface

This thesis contains the work of a research study conducted by Mr. Angelo Graffos under the supervision of Dr. Michael Hunt, and with guidance from Drs. David Wilson, Sima Zakani and Jean-Francois Esculier. Data collection was performed by the candidate with assistance from Maryam Mohtajeb. The study design, data processing, data analysis and writing of the manuscript were primarily the work of the candidate. Select data from this thesis will be submitted for publication in a peer-reviewed journal.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

ACL	Anterior cruciate ligament
ANOVA	Analysis of variance
ASIS	Anterior superior iliac spine
BMI	Body mass index
BW	Body weight
COSMIN	COnsensus-based Standards for the selection of health Measurement INstruments
CT	Computerized tomography
EMG	Electromyography
FABER	Flexion abduction external rotation
FADIR	Flexion adduction internal rotation
FAI	Femoroacetabular impingement
FMS	Functional Movement Screen
HAGOS	Copenhagen Hip and Groin Outcome Score
Ht	Height
Hz	Hertz
IK	Inverse kinematics
LCEA	Lateral centre edge angle
MRA	Magnetic resonance arthrography
MRI	Magnetic resonance imaging
NRS	Numerical rating scale
PSIS	Posterior superior iliac spine
ROM	Range of motion
SPSS	Statistical Package for the Social Sciences
STS	Sit-to-stand
vGRF	Vertical ground reaction force

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Chapter 1: Introduction

1.1 Hip Joint

The hip joint is one of the most mobile joints of the human body and is able to move freely in 3 planes (Neumann, 2010). In the sagittal plane, the hip can undergo flexion and extension. In the frontal plane, abduction and adduction occurs, and in the transverse plane, internal (or medial) rotation and external (or lateral) rotation happens. It is a ball and socket joint with 21 muscles crossing it, providing both movement and stability (Neumann, 2010). In addition, there are ligaments, tendons, fascia and soft tissue that act to stabilize the hip joint during motion, including the iliofemoral ligament which is the strongest ligament in the human body (Neumann, 2010). When these structures are negatively affected, or the surrounding ligaments and muscles are tight or weak, this can cause abnormal force distribution throughout the joint. This abnormal force distribution can potentially lead to, or contribute to, degenerative changes in the cartilage, bone and surrounding connective tissue (Neumann, 2010). The degenerative changes in these connective tissues can be indicative of certain pathological conditions (Neumann, 2010). One of these pathological conditions is femoroacetabular impingement (FAI).

1.2 Femoroacetabular Impingement

Femoroacetabular impingement is a patho-mechanical hip condition or syndrome that involves an abnormal contact between the femur and the acetabulum (Zhang et al., 2015). FAI can present as one of three types of hip impingement; cam morphology, pincer morphology or mixed type. Cam FAI is radiologically presented as an aspherical femoral head and/or an abnormal femoral head-neck offset (Agricola et al., 2013; Ganz et al., 2003). The abnormally shaped femoral head can abut into the acetabulum, specifically into the anterosuperior and lateral aspect of the acetabulum, when engaging in high amounts of hip flexion, adduction and/or internal rotation (Ganz et al., 2003). Pincer FAI is an acetabulum abnormality, and may present as a local anteriorly rotated or retroverted acetabulum, or more globally as protrusio acetabuli or coxa profunda (Ganz et al., 2003). Protrusio acetabuli refers to the femoral head being located more medially, past the pelvic ilioischial line, and coxa profunda refers to a deep acetabular socket where the acetabulum is located more medially, past the ilioischial line (Bardakos and Villar, 2009). The most common type of FAI is the mixed morphology, with both cam and pincer characteristics seen in varying degrees (Anderson et al., 2013).

FAI was first introduced as a potential risk factor for 'idiopathic' hip osteoarthritis (OA) in 2003 (Ganz et al., 2003). However, an impingement similar to FAI, where the femoral neck abutted against the anterior acetabular margin, was first reported by Smith-Petersen in 1936 (Smith-Petersen, 2009). This impingement was theorized from the hip pain a patient diagnosed with bilateral intrapelvic protrusion of the acetabulum was experiencing, and the potential of this diagnosis to lead to 'traumatic arthritis' if not treated. In 1965, Murray first stated a potential association between a common minor anatomical abnormality he termed femoral head 'tilt deformity' and primary hip osteoarthritis development (Murray and Duncan, 1971). Similar to the 'tilt deformity', Harris and colleagues used the term 'pistol-grip deformity' in 1979 to describe an abnormal femoral head that was present in 5 out of 8 hips originally proposed to have developed from 'idiopathic' hip osteoarthritis (Harris et al., 1979). The 'pistol-grip deformity' became one of the more common reasons for developing hip OA, along with acetabular dysplasia, and was present in over 90% of patients tested for 'idiopathic' hip osteoarthritis (Harris, 1986). In 2003, the 'pistol-grip deformity' was acknowledged as a characteristic of cam FAI by Ganz and colleagues (Ganz et al., 2003). Since 2003, research in FAI has considerably increased due to its potential contribution to hip osteoarthritis, and of the three types, the cam morphology has been shown to be most strongly linked to hip OA (Agricola et al., 2013).

1.3 Diagnosis of FAI

The diagnosis of FAI includes many components including patient history, clinical testing results and radiological findings (Zhang et al., 2015). People with FAI usually present with a history of groin pain. The groin is the most common location of pain, but other areas of pain may include the low back, thigh, and buttock (Clohisy et al., 2009). Common clinical testing associated with FAI diagnosis includes the flexion, adduction and internal hip rotation (FADIR) and the flexion, abduction and external hip rotation (FABER) tests (Reiman et al., 2017; Zhang et al., 2015). The FADIR, or the anterior impingement test, involves the patient lying supine and the hip being flexed to 90˚ while passively adducting and internally rotating the hip at the same time. On a similar note, the patient lies supine and the hip is brought into passive flexion, abduction and external rotation for the FABER test. A positive result on both of these tests is the reproducibility of the pain that the patient experiences on a daily basis.

With regards to imaging, there are multiple techniques to assess the presence of FAI. These techniques include axial and radial magnetic resonance imaging (MRI), Dunn view, frog-leg lateral and anteroposterior x-ray view, computerized tomography (CT) and magnetic resonance arthrography (MRA) (Leunig et al., 2007; Reiman et al., 2017). The anteroposterior view is useful for calculating the lateral center edge angle (LCEA) and the Tonnis angle, measures for detecting radiological signs of pincer FAI (Pun et al., 2015). LCEA and Tonnis angles aid in indicating acetabular over-coverage, and a LCEA >40˚ and Tonnis angle <0˚ demonstrate global acetabular over-coverage. The frog-leg lateral view is useful for detecting radiological signs of cam FAI like the alpha angle, head-neck offset and the femoral sphericity (Pun et al., 2015; Zhang et al., 2015).

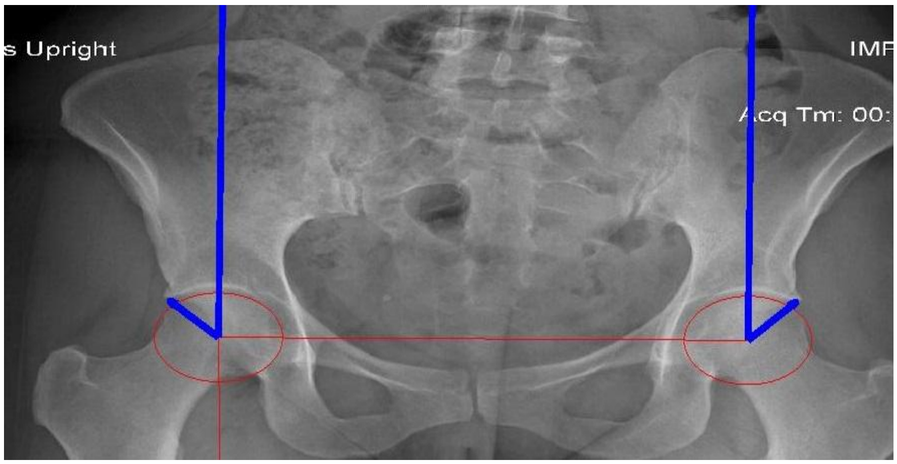

Figure 1.1: Lateral centre edge angle. The lateral centre edge angle is the angle between the blue lines in the above photo, where one blue line runs through the centre of the femoral head, perpendicular to the transverse axis, and the other blue line is from the centre of the femoral head to the most superolateral aspect of the acetabulum (Ratzlaff et al., 2016). **With permission from the IMPAKT-HIP Study.**

The alpha angle is an index of femoral head sphericity, and is measured as the angle between a line along the proximal femoral neck, starting from the center of the femoral head, and a line from the center of the femoral head to the first anterior point where the femoral head-neck junction extends beyond the femoral head radius (Chakraverty and Snelling, 2012). An alpha angle greater than 55˚ has been a common threshold for indication of osseous abnormalities at the femoral head-neck junction, and thus the presence of cam FAI (Martin and Katz, 2012). However, an article in the same year by Sutter and colleagues (2012) reported that there was a large overlap in the alpha angle values present in asymptomatic volunteers and people with symptomatic FAI. Because of this overlap in alpha angles, alternative methods other than radiological techniques are needed to discern differences between these populations.

People with a positive sign (indication of pain) on a clinical examination for FAI like FADIR and radiological symptoms like an alpha angle greater than 55˚, and LCEA and Tonnis angles >40˚ and <0˚, respectively, are termed symptomatic FAI. There are, however, populations where they are asymptomatic upon going through clinical testing but present with radiological findings of FAI (Frank et al., 2015; Hack et al., 2010; Jung et al., 2011; Mascarenhas et al., 2016). These populations are termed asymptomatic FAI.

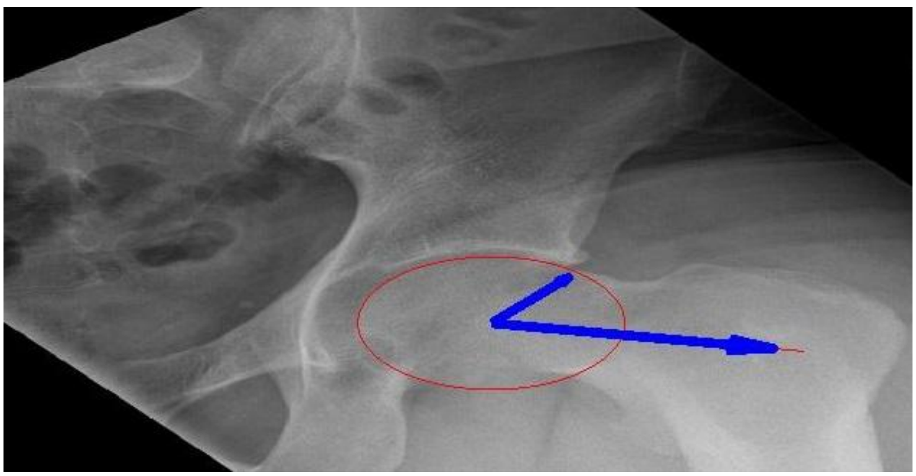

Figure 1.2: Alpha angle. The alpha angle is the angle between the two blue lines in the above photo, where one blue line is the femoral neck axis and the other blue line is extended from the centre of the femoral head to the first instance of femoral head asphericity (Ratzlaff et al., 2016). **With permission from the IMPAKT-HIP Study.**

1.4 Epidemiology of FAI

1.4.1 Etiology of FAI

Theories of the etiology of FAI over time have examined the influence of genetics, mechanical adaptations that have developed following activities that involve repetitive hip flexion and/or internal rotation movements, and other developmental pathologies like slipped capital femoral epiphysis and Legg-Calvé-Perthes disease (Chaudhry and Ayeni, 2014; Kuhns et al., 2015; Packer and Safran, 2015). One current theory involves the developmental adaptations during adolescence from repetitive physical activity or sporting activities (Packer and Safran, 2015). This theory was originally hypothesized in 1971 (Murray and Duncan, 1971). They found that increased athletic activity in adolescent athletes during sports programs like cross-country, track running, jumping and gymnastics led to a higher presence of the pistol-grip deformity or the 'tilt deformity of the femoral head', was more prevalent in males compared to females, and was positively correlated with hip arthritis (de Silva et al., 2016; Murray and Duncan, 1971; Packer and Safran, 2015). As described earlier, the pistol-grip deformity or an aspherical femoral head, is a characteristic of the cam morphology (Ganz et al., 2003). This theory was later described as a biomechanical theory in a review article by Zadpoor (2015). The theory states that the mechanical loads experienced during intense physical activity will lead to stress in the growth plate and surrounding areas, (areas of the femur not accustomed to high musculoskeletal loads) and these areas will experience large loads from the extreme ranges of hip motion. Subsequently, these large loads will induce a stimulus for bone growth which will then result in the femur acquiring an abnormal shape. Despite these possible factors contributing to the development of FAI, the exact etiology of FAI is still unclear (Chaudhry and Ayeni, 2014).

1.4.2 Prevalence of FAI

A recent systematic review by Mascarenhas and colleagues (2016) analyzed 35 previous articles with 4169 symptomatic, non-athletic FAI hips. The average prevalence of symptomatic cam morphology was 49%, symptomatic mixed morphology was 40.2%, and symptomatic pincer morphology was 28.5%. Another study by Röling, Mathijssen, and Bloem (2016) found a 17%

prevalence of radiographic FAI with groin pain in the general population. In addition to symptomatic populations, athletes and the general population include people with asymptomatic FAI (Frank et al., 2015; Hack et al., 2010; Jung et al., 2011; Mascarenhas et al., 2016). A recent systematic review examined 26 studies and 2,114 hips and found, on average, a prevalence of asymptomatic cam FAI in 54.8% of athletes and 23.1% of the general population (Frank et al., 2015). Additionally, a prevalence of 67% was found across the 26 studies for pincer FAI. Another systematic review found a prevalence of 22.4% for cam-type impingement in asymptomatic individuals, a prevalence of 57% for pincer FAI, and a prevalence of 8.8% for mixed FAI in the 7282 hips analyzed (Mascarenhas et al., 2016).

With regards to athletes, cam impingement is commonly seen in athletes playing sports like football, ice hockey, soccer and basketball (Packer and Safran, 2015). In football, a prospective study by Kapron et al. (2011) examined 67 male collegiate athletes, and 72% of the 134 hips analyzed had an alpha angle greater than 50˚ and 64% had a decreased femoral head-neck offset. For soccer players, a study by Gerhardt and colleagues (2012) retrospectively analyzed anteroposterior and frog-leg lateral hip radiographs of 95 elite male and female elite soccer athletes. They found cam characteristics in 68% of males (51/75) and in 50% of females (10/20). The cam characteristics included an alpha angle >55˚, loss of femoral head sphericity and excessive bone formation at the femoral head-neck junction.

In addition to cam characteristics present in athletes, pincer morphology was found in 51.2% of the 1389 athletic hips analyzed in a recent systematic review (Mascarenhas et al., 2016). Furthermore, two studies included by Mascarenhas and colleagues (2016) reported an average of 57.1% of athletes that exhibited mixed FAI characteristics. In addition to football, soccer, ice hockey and basketball, radiographic evidence of FAI is also present in tennis and baseball players (Philippon et al., 2012; Philippon et al., 2007; Philippon et al., 2016; Tran et al., 2013). Like the sports previously mentioned, tennis is a high demand sport that involves multidirectional movements and repeatedly puts the hip in positions of flexion or internal rotation (Algarni, 2013; Keogh and Batt, 2008). Furthermore, in an abstract by Cotorro et al. (2014), the researchers screened 148 elite youth tennis players and found that 62% had a hip that was at risk of acquiring FAI. This was based on findings like positive impingement tests in one or both hips and decreased hip internal rotation. With regards to baseball, it also involves movements that put the hip in positions of impingement, like a catcher in constant hip flexion and internal rotation, and a pitcher lunging forward to throw the ball to the batter (Allen et al., 2002; Weber et al., 2017). Overall, the prevalence of FAI is fairly high, both in the general population and in the athletic population, thus the need for investigating and researching further. One way of accomplishing this, is by analyzing movements that are common in these populations.

1.5 Biomechanical Studies on FAI Populations

To analyze how a movement is performed, biomechanical studies are used to understand the kinematics and kinetics. By looking at joint angles and excursion (kinematics), and forces impacting one's joints (ground reaction forces) and a measure of indirect loads on the joint (joint moments), both comprising kinetics, one is able to determine the requirements and demands of the human body to execute a given movement. More importantly, a biomechanical analysis will allow for comparisons in movement performance between healthy and clinical populations like FAI to discern any important differences that could further the understanding of FAI's patho-mechanical mechanism, etiology and rehabilitation.

1.5.1 Symptomatic FAI

There are multiple studies that have analyzed the biomechanics of movements in symptomatic FAI populations. In order from low hip flexion to high hip flexion, the movements analyzed include: walking, stair-climbing, single-leg step-down, drop-landing, sit-to-stand, and squat.

In gait and stair-climbing, movements that require small amounts of hip flexion (30˚ and 60˚, respectively) (Hammond et al., 2017; Hunt et al., 2013), there are conflicting, but few biomechanical differences between symptomatic FAI and asymptomatic healthy controls.

1.5.1.1 Walking

A study by Kennedy and colleagues (2009) investigated the biomechanics of walking in 17 people with unilateral cam FAI and 14 healthy controls. There were no statistically significant differences in the peak external hip moments in the sagittal, frontal and transverse planes, but people with cam FAI had statistically significantly lower peak hip abduction angles, less hip frontal plane excursion, lower hip sagittal plane excursion, and less pelvis frontal plane excursion. In 2013, Hunt and colleagues conducted a cross-sectional study analyzing the gait kinematics and kinetics of 30 people with cam and pincer FAI and 30 healthy controls (Hunt et al., 2013). The results indicated that the participants with FAI had statistically significantly less peak hip extension, adduction and internal rotation, and the peak external hip flexion and external rotation moments were statistically significantly lower.

Kumar and colleagues (2014) analyzed walking kinematics and kinetics in participants with and without cam FAI, and FAI participants with and without cartilage lesions. Peak kinematic and kinetic variables and joint excursions for the hip in all 3 planes were compared and there were no statistically significant differences in any of these variables when comparing between people with and without FAI, or between individuals with and without cartilage lesions. Similar findings were seen in a walking study by Diamond and colleagues (2016) where there were no statistically significant group differences for peak external joint moments in any plane for the hip. Furthermore, there were no statistically significant differences between groups for peak hip flexion angle during stance or swing, peak extension angle during swing, or any of the peak frontal or transverse plane angles. However, the one statistically significant finding was that the group with cam or mixed FAI walked with less hip sagittal plane excursion during the entire cycle than the asymptomatic control group. Despite the conflicting findings, the literature as a whole appears to suggest that there are few differences seen in walking, so investigating movements requiring larger hip flexion angles may reveal more differences.

1.5.1.2 Stair-climbing

With regards to stair-climbing, there are three known studies comparing the stair-climbing biomechanics of people with FAI to healthy controls (Diamond et al., 2018; Hammond et al., 2017; Rylander et al., 2013). Rylander and colleagues (2013) studied the preoperative and postoperative biomechanical differences in people with FAI (n=17) following arthroscopic hip reshaping surgery, compared to 17 healthy controls. Post-surgery, some variables were not restored to “normal”, as when compared to controls. Specifically, the hip sagittal plane excursion remained statistically significantly decreased in the FAI group compared to controls, the peak hip internal rotation remained statistically significantly smaller compared to controls, and the pelvis transverse plane excursion and the peak pelvis anterior tilt remained statistically significantly increased in FAI compared to controls. Conversely, in an exploratory cross-sectional study by

Hammond and colleagues (2017), there were minimal differences in 20 individuals with FAI compared to 20 controls. The results indicated that the participants with FAI showed statistically significantly larger peak trunk forward flexion, larger peak external hip flexion moment, and smaller peak external knee flexion moment. There were, however, no other statistically significant between-group kinematic differences at the hip, knee or ankle in any plane and no other statistically significant kinetic differences. Finally, in another exploratory study by Diamond et al. (2018), they examined differences in step ascent biomechanics between 15 participants with cam or combined (cam and pincer) FAI and 11 healthy non-FAI controls. When comparing between the groups, the participants with FAI exhibited statistically significantly greater peak lateral trunk lean during single-limb support towards the affected side, greater peak ipsilateral pelvis rise on foot contact with the step and on single-limb support, greater peak hip adduction on foot contact with the step and smaller peak hip external rotation moment than the controls. There were, however, no other statistically significant differences between the other 21 biomechanical variables that were tested. Like walking, there appears to be minimal biomechanical differences between FAI populations and healthy populations during stair climbing.

1.5.1.3 Single-leg Step-down

There has been one study that has analyzed the biomechanics of the single-leg step-down in individuals with FAI and in individuals without hip pain (Lewis et al., 2018b). Lewis et al. (2018b) reported multiple kinematic outcomes on twenty participants with FAI and forty participants without hip pain while stepping down from a 16 cm high box and touching the ground with one’s heel. The speed of the movement was also standardized with a metronome, where the speed to be maintained was 60 beats/minute. Hip flexion and adduction, knee abduction, pelvis anterior tilt and drop, thigh flexion and adduction, and shank flexion and abduction were all analyzed at 60° knee flexion, and the only two variables that showed statistically significant differences between the two groups were hip flexion and pelvis anterior tilt. More specifically, the group with FAI exhibited greater hip flexion and greater pelvis anterior tilt during the single-leg step-down compared to the group without hip pain. Compared to the previously mentioned movements, even fewer differences are seen with the single-leg step-down movement between symptomatic FAI and healthy populations.

Because of the minimal biomechanical differences present in walking, stair climbing and single-leg step-down between these populations, this has led others to investigate more challenging movements requiring larger hip flexion angles, like drop-landing, sit-to-stand and maximal squat, to explore the potential effects of FAI on movement.

1.5.1.4 Drop-landing

A higher demanding and higher impact task than walking, stair climbing and single-leg step-down, drop-landing is a movement (close to 80° of hip flexion) that was assessed in a study by Kumar and colleagues (2014). The performance of this task was compared between 8 healthy controls and 7 participants with FAI (total of 15 participants), and was also compared between the participants with FAI and cartilage lesions (n=6) and the rest of the participants (n=9). To perform the movement, the participants were instructed to drop from a 12in high platform, land with both feet on the two force platforms and then jump as high as possible. When comparing between controls and the group with FAI, the only statistically significant difference was that the participants with FAI landed with their feet closer together. There were no statistically significant differences in hip joint sagittal, frontal and transverse plane excursions, or peak hip angles, moments and powers. However, when comparing between the group with FAI and cartilage lesions and the group without cartilage lesions, the group with FAI and cartilage lesions exhibited statistically significantly smaller peak hip internal rotation, smaller base of support and greater peak hip adduction. Regardless of whether the FAI group had cartilage lesions or not, the comparison to a control group revealed minimal differences, thus the investigation of a movement requiring greater hip flexion is warranted to potentially unveil more differences.

1.5.1.5 Sit-to-stand task

A task that requires considerably more hip flexion (closer to 90˚) than walking, stair-climbing or single-leg step-down is the sit-to-stand (STS) task (Eitzen et al., 2014; Samaan et al., 2017). Importantly, getting up from a low chair has been reported as a source of hip pain by people with FAI (Samaan et al., 2017). Samaan and colleagues (2017) conducted a cross-sectional study that looked at joint kinetics and task performance in 17 people with FAI (8 cam, 3 pincer and 6 mixed) and 31 controls. The participants performed the STS task over a height-adjustable box that was adjusted to the height of the participants' medial femoral condyle. The biomechanical variables analyzed included peak sagittal plane knee joint moment, peak sagittal plane hip joint moment and peak sagittal plane ankle joint moment, and none of these dependent variables were statistically significantly different between the two groups. Moreover, the different FAI subtypes did not show statistically significant differences between one another for any of these dependent variables. Overall, at least from a kinetic standpoint, people with FAI perform the STS task similarly to a healthy population. Because only kinetics were examined, further investigation is required to understand how movements with high hip flexion are performed by FAI populations. A movement with similar amounts of hip flexion that has received more research may present with important findings and differences in FAI populations. One such movement is the squat.

1.5.1.6 Squat

The squat is another type of movement that nears the end range of available hip flexion, requiring roughly 100˚ (Bagwell et al., 2016). There are multiple studies and a thesis document, examining the biomechanics of this task in people with symptomatic FAI. In a cross-sectional study by Lamontagne and colleagues (2009), they tested the kinematics of the deep squat in 15 people with cam FAI and 11 controls. The participants squatted over a height-adjustable bench that was adjusted to 1/3 of the person's tibial plateau's height from the ground. Throughout the movement, the variables analyzed included peak hip angle in each plane at the maximum depth, the peak pelvis angle during descent, ascent and at peak depth, the total pelvis excursion in each plane, and the maximum squat depth attained. It was found that the participants with FAI had decreased pelvis sagittal plane excursion compared to the controls, and squatted less deep compared to the controls, but there were no statistically significant differences in any of the hip angles at the maximum squat depth.

Kumar et al. (2014) conducted a cross-sectional study that looked at the kinematics and kinetics of the squat in 7 unilateral symptomatic FAI and 8 healthy volunteers with no FAI. The squat was performed 5 times, but the distance between the feet was not controlled and the participants were not told to maintain heel contact throughout the movement. The FAI group had statistically significantly greater peak hip adduction and greater peak hip internal rotation moment than the control group. Bagwell et al. (2016) conducted a cross-sectional study comparing the hip kinematics and kinetics in 15 people with unilateral symptomatic cam FAI and 15 controls. Similar to the previous squat studies mentioned above, there was statistically significantly less squat depth and increased anterior pelvis tilt in the FAI group. They also found statistically significantly decreased peak hip internal rotation, decreased peak femur flexion at the time of peak hip flexion, and a statistically significantly decreased mean hip extensor moment in the FAI group when compared to controls. There were, however, no statistically significant differences in peak hip flexion or peak hip abduction between the two groups.

In a recent study by Diamond et al. (2017), they examined the hip kinematics and kinetics, and trunk and pelvis kinematics of two types of squats, unconstrained and constrained. The unconstrained squat involved the participant's preferred squat strategy with their arms extended anteriorly, and the constrained squat was similar to the unconstrained squat except for the limitation of forward trunk lean and pelvis sagittal plane excursion with the use of a pole placed directly in front of the participants. These squats were performed by 15 symptomatic cam or combined FAI participants and 14 non-FAI controls. With respect to both squat tasks, there were no statistically significant differences in squat depth. For the unconstrained squat, the statistically significant findings included the FAI group exhibiting slower descent speed, greater ipsilateral pelvis rise at peak squat depth, and peak hip flexion moment throughout the squat. After adjusting for squat speed, greater ipsilateral pelvis rise at peak squat depth was the only variable that was still statistically significant. However, the constrained squat task was also performed at similar speeds between groups and more statistically significant findings became evident. Compared to the control group, the FAI participants demonstrated greater ipsilateral pelvis rise, and a decreased hip external rotation moment and hip transverse plane excursion during descent. Moreover, greater hip adduction values were seen in the FAI group, a finding similar to Kumar et al. (2014) but with the squat task being unconstrained. Overall, the squat revealed more statistically significant differences between FAI and healthy populations and possibly some important consistent findings (decreased squat depth and pelvis sagittal plane excursion). Thus, further investigation of movements with similar amounts of hip flexion to the squat, is warranted.

The biomechanical literature on symptomatic FAI populations is limited, with a combination of contradictory and common findings in low hip and high hip flexion movements. However, it is still not clear whether biomechanical differences between symptomatic FAI and healthy non-FAI populations are solely due to pain; thus the study of asymptomatic FAI populations is important to determine other possible reasons for biomechanical differences and for better understanding the condition. Despite the high prevalence of asymptomatic FAI populations in the general and athletic populations, there is a paucity of biomechanical research in these individuals.

1.5.2 Asymptomatic FAI

There are three known studies that have reported the biomechanics of movement in asymptomatic FAI populations. The first paper, a thesis document by Dwyer (2014), analyzed the kinematics and kinetics of level walking and maximal depth squatting in people with symptomatic FAI, asymptomatic FAI and controls. Fifteen symptomatic FAI, 17 asymptomatic FAI and 14 control participants performed these two movements, and there were no statistically significant differences between the two groups in the kinematic and kinetic variables that were analyzed.

The second study looked at the differences in squatting kinematics between symptomatic FAI, asymptomatic FAI and healthy controls (Ng et al., 2015). This cross-sectional study analyzed 12 symptomatic cam FAI, 17 asymptomatic FAI and 14 asymptomatic controls and examined pelvis sagittal plane excursion and maximal squat depth. With regards to these two variables, the differences between the three groups were not statistically significant. However, the symptomatic group showed less squat depth and lower pelvis sagittal plane excursion than the other two groups. Thus, while there may not be statistically significant differences between these populations while walking, there may be statistically significant differences in kinematics and kinetics at deeper squat depths.

The third study also examined differences in deep squatting kinematics between 16 symptomatic cam FAI, 18 asymptomatic cam FAI and 18 healthy controls, along with recording hip and thigh musculature electrical activity (EMG – electromyography) (Catelli et al., 2018). Similar to previously mentioned protocols, each participant squatted at their self-selected speed and with their feet facing forward and heels remaining on the ground. Moreover, an adjustable bench was placed below the participants, at 1/3 the height of the participant's tibia from the ground. Several statistically significant differences arose, where there were between-group differences in squat depth, pelvis sagittal plane excursion, peak hip flexion, hip sagittal plane excursion and biceps femoris, semitendinosus, rectus femoris and gluteus maximus muscle activity. The sFAI group squatted less deep than both the aFAI group and control group. During the descent phase of the squat, the authors reported that the sFAI group had smaller pelvis sagittal plane excursion than the aFAI and control groups, lower peak hip flexion than the control group, and lower hip sagittal plane excursion than the control group. Also during the descent phase, the biceps femoris and semitendinosus activity was larger in the sFAI group than the aFAI group. For the ascent phase of the squat, the sFAI group had lower pelvis sagittal plane excursion than the control group, lower peak hip flexion than the control group and lower hip sagittal plane excursion than the control group. Moreover, the biceps femoris and semitendinosus activity was larger in the sFAI group than the aFAI group and the gluteus maximus activity was larger in the sFAI group than the aFAI and control groups. Further research in movements requiring large amounts of hip flexion is warranted to elucidate biomechanical differences between symptomatic FAI, asymptomatic FAI and non-FAI populations as more statistically significant differences arose when Catelli et al. (2018) examined the deep squat.

While there are research studies examining the biomechanics of movements requiring high amounts of hip flexion, there is a paucity of research studies in movements that require near terminal hip flexion and are sport-related movements. Apart from the squat, there are no other studies in FAI populations that have biomechanically examined movements that occur in sports. Moreover, in a recent systematic review and meta-analysis that examined the lower limb biomechanics literature in FAI populations, King et al. (2018) reported few biomechanical differences between FAI and non-FAI populations in the everyday activities that have been studied to date (e.g. walking, squat, stair-climbing, sit-to-stand and drop-landing). Because of these findings, the authors recommended investigation of sport-specific movements for future research to potentially aid in discerning more biomechanical differences between FAI and non-FAI populations in these higher impact activities. Examining sport-specific movements is also important from a FAI perspective, as there is a potential link between repetitive high hip flexion sport-related activity during adolescent bone growth and acquiring FAI (Frank et al., 2015). Finally, as previously mentioned, the prevalence of radiographic cam, pincer and mixed FAI is quite high in the athletic population (Mascarenhas et al., 2016). Thus, the analysis of a sports-related movement in a FAI population lends itself for investigation, and one such movement is the lunge.

1.6 Lunging

The lunge is a movement commonly performed during sports (Casartelli et al., 2018; Draovitch et al., 2012; Hiroichi, 2004; Lim et al., 2017; Rajkumar, 2015; Varner et al., 1990). Various lunge variations, including but not limited to, the forward, reverse, lateral and angled forward walking lunge, mimic positions seen in sports like tennis, rugby, basketball, skiing, soccer and hockey (Keogh, 1999). Some examples may include the athlete lunging forward to volley in tennis, lunging at an angle or laterally while sidestepping or cutting in basketball and soccer, and lunging forward and diagonally while pitching and fielding a ground ball in baseball, respectively. Because the lunge is a sport-specific movement, the study of this movement in a FAI population is warranted due to the high prevalence of this condition in athletes.

In addition to the lunge being a sport-related movement, the lunge is a motor task common in everyday living (Scheys et al., 2013), and is thus a relevant task to be analyzed. Because people with FAI express difficulty and experience pain while walking, a low hip flexion everyday movement, it is expected that the high amounts of hip flexion in the lunge would likely aggravate and reproduce everyday pain in people with FAI (Kolber et al., 2015).

Furthermore, the lunge is a bilateral closed kinetic chain exercise that is commonly used in exercise, sport training and rehabilitation settings (Riemann et al., 2013; Riemann et al., 2012). There are many variations of lunge technique like changing one's trunk position, shank angle and step length while lunging, and there are many types of lunges like the forward, reverse, lateral, and stationary lunge (Farrokhi et al., 2008; Hofmann et al., 2017; Riemann et al., 2013;

Schütz et al., 2014). In relation to sport, the lunge is an exercise that is used to prevent hip and knee hockey injuries (Wolynski et al., 1998), is used in training programs by soccer players (Santana, 2002), and is helpful towards improving dynamic balance in athletes of certain sports like rugby, basketball and hockey (Keogh, 1999).

1.6.1 Lunge Literature

Most of the research literature on lunging is in healthy populations; however, there is one study that looked specifically at the biomechanics of the forward lunge in people with a hip pathology (Dwyer et al., 2016), and one study that has visually rated the movement quality of the frontal and hop lunge in a FAI population (Casartelli et al., 2018). Dwyer and colleagues (2016) looked to see if there were differences in vertical ground reaction forces (vGRF) or electrical recording of muscle activity of the gluteus medius, gluteus maximus, adductor longus and rectus femoris muscles between a symptomatic group with unilateral acetabular labral tears and an asymptomatic control group. Ten of the seventeen participants with labral tears did not experience pain while performing the forward lunge while the other seven expressed discomfort and were unsure about the pain numerical value. The researchers found statistically significantly decreased average gluteus maximus EMG activity during lunge ascent and statistically significantly increased contact time while performing the lunge in the labral tears group compared to the healthy controls. These results are important to be considered as they provide some insight into the effect of FAI on lunging as acetabular labral tears are typically consequences of having cam and pincer FAI (Rylander et al., 2010).

In a recent methodological study by Casartelli et al. (2018), three physiotherapists of varying clinical experience (29 years, 6 years and <1 year) visually rated multiple movements including the frontal and hop lunge, squat, single-limb standing, bridge and plank, in 34 participants with symptomatic FAI. Using two visual rating subscales along with one video camera, the overall movement quality relating to the whole body, the movement quality in relation to individual segments and the association between movement quality, hip abductor strength and pain were all assessed. Compared to the other movements, more participants with FAI did not exhibit proper movement quality with respect to the frontal and hop lunge and the squat. Furthermore, there was a relationship seen between hip abductor strength and movement quality, where the hip abductor strength of poor performers (with respect to overall movement quality) of the frontal and hop lunges were statistically significantly weaker than the hip abductor strength of good performers (with respect to overall movement quality) of the frontal and hop lunges. The results of this study provide a stronger rationale for the analysis of a lunge in a FAI population as the weaker movement quality (derived from a visual analysis) and hip abductor strength in people with symptomatic FAI may translate into discovering important biomechanical differences when conducting motion capture between the asymptomatic FAI and control groups.

From a treatment perspective, there are only a handful of research articles that include the lunge as a recommended exercise in post-arthroscopy rehabilitation (Pierce et al., 2013; Wahoff et al., 2014; Wahoff and Ryan, 2011). However, a recent study examined the efficacy of a pre-hip arthroscopy exercise intervention in people with FAI that included the lunge as an exercise, and deemed the intervention safe and feasible (Guenther et al., 2017). Despite the presence of the lunge in pre- and post-arthroscopy rehabilitation programs, it is not well understood how people with FAI perform a lunge from a biomechanical perspective.

Overall, the lunge is a common functional (Casartelli et al., 2018) and sport-relevant movement that also plays an important role in rehabilitation and training for FAI. The repetitive nature of performing the lunge during everyday life and sporting activities may also provide some insight into the patho-mechanism and etiology of FAI, respectively. By analyzing a movement with high degrees of hip flexion, more information may be learned regarding terminal hip motion and restrictions in hip motion due to impingement. With respect to the etiology, the analysis of a common sport maneuver could help explain the underlying reason why performing constant sporting activities during adolescent bone growth could lead to cam FAI and possibly hip osteoarthritis in the future (Murray and Duncan, 1971). As a common exercise in rehabilitation and training, it is also important to have a full understanding of joint excursion and load while performing a lunge, as this will aid healthcare practitioners to properly prescribe this exercise, and any variation of it, for rehabilitative or training purposes in FAI populations. Thus, for all of these reasons, the analysis of the lunge movement is warranted in a FAI population. However, the lunge is a general movement common to many sports, so the exploration of a lunge more specific to the FAI population, with respect to its pathology and sport-relevance, is needed to better understand the condition itself.

1.6.2 The 45° Cross-body Lunge

The 45° cross-body lunge is a sport-specific movement (Handzel, 2003) that occurs predominantly in the sagittal and frontal planes and requires the action of thigh, gluteal, and core muscles (Roetert and Kovacs, 2011). This lunge is very common in tennis, where it is used to perform ground-strokes and volleys (McClellan and Bugg, 1999; Roetert and Kovacs, 2011). This is especially true of volleys, where the player must either react quickly and lunge across, or lunge to a ball that is out of reach. Moreover, the 45˚ cross-body lunge can be performed while lunging diagonally to field a ball in baseball, tackle a running back in football or reach for a loose ball in basketball (Allen et al., 2002). The 45˚ cross-body lunge is also very similar to the crossover step or cut, a movement common in sports like basketball and soccer (Houck, 2003), the third most common movement in hockey (Manners, 2004) and a movement that is also typically performed at 45˚ (Houck, 2003). From a rehabilitative standpoint, this type of lunge is a variation of the diagonal lunge, which is common in warm-up, flexibility and training programs for hockey athletes (Twist, 2007), and is present in rehabilitation post-anterior cruciate ligament (ACL) reconstruction surgery (Manske et al., 2012), an injury common to basketball and soccer players (Houck, 2003). Despite the crossover step and 45˚ cross-body lunge being more commonly associated with knee joint rehabilitation in the literature, this movement is particularly relevant from a FAI perspective.

The 45˚ cross-body lunge should be studied in a FAI population for the following reasons. Firstly, the crossover movement and 45˚ cross-body lunge is common in basketball, soccer, hockey, football, and tennis; sports involving athletes that present with radiographic signs of FAI (Packer and Safran, 2015; Philippon et al., 2016). Investigation of this movement could provide some insight into the etiology of FAI, specifically the biomechanical theory originally proposed by Murray and Duncan in 1971. Specifically, by analyzing a commonly performed movement in sports, the link between vigorous sporting activity during adolescent growth and cam FAI may be better understood. Secondly, the 45˚ cross-body lunge requires near terminal hip movement in the sagittal and frontal plane, with roughly 100˚ of hip flexion and 20˚ of hip adduction (according to pilot data). When the hip engages in a movement with high amounts of hip flexion and adduction, the femoral head comes in contact, or articulates with, the acetabular rim (Ganz et al., 2003). When the femoral head articulates with the acetabular rim, particularly in the anterosuperior or lateral region of the acetabulum (Ganz et al., 2003), impingement is likely to occur (Pedersen et al., 2005) and pain may be elicited. By looking at a movement that will likely put the hip in an impingement position, with possible resulting pain, more important information can be learned regarding the patho-mechanism of FAI and possible biomechanical differences between symptomatic FAI, asymptomatic FAI and non-FAI populations than analyzing a lunge only in the sagittal plane (e.g. a forward lunge). Because of all these reasons, and the fact that the lunge has not been investigated in FAI populations, this proposed study will investigate the biomechanics of the 45˚ cross-body lunge.

1.7 Objective and Hypotheses

1.7.1 Objective

The objective of this exploratory, cross-sectional study was to conduct a kinematic and kinetic analysis of the lower limb, hip, pelvis and trunk during performance of the 45˚ cross-body lunge in people with symptomatic FAI, asymptomatic FAI, and non-FAI controls.

1.7.2 Hypotheses

1. With regards to pelvis kinematics, people with symptomatic FAI will exhibit decreased sagittal plane excursion and decreased frontal plane excursion during the entire 45˚ cross-body lunge movement compared to the asymptomatic FAI and non-FAI groups.
2. With regards to hip kinematics and kinetics, people with symptomatic FAI will exhibit decreased lead hip flexion and adduction at peak knee flexion, and an increased peak

external hip flexion moment while lunging compared to the asymptomatic FAI and non-FAI groups.

3. People with symptomatic FAI will exhibit increased trunk flexion at peak knee flexion while lunging compared to the asymptomatic FAI and non-FAI groups.
4. People with symptomatic FAI will exhibit a decreased lunge depth compared to the asymptomatic FAI and non-FAI groups.
5. People with symptomatic FAI will have increased contact time with the force platform, thus performing the lunge at a slower speed, when compared to the asymptomatic FAI and non-FAI groups.
6. People with symptomatic FAI will exhibit smaller lead limb vertical ground reaction forces and larger trail limb vertical ground reaction forces on both lunge descent and ascent, when compared to the asymptomatic FAI and non-FAI groups.

Chapter 2: Methods

2.1 Study Design

This was an exploratory cross-sectional study utilizing a between-group design, where hip, knee and ankle kinematics and kinetics, pelvis and trunk kinematics, and vertical ground reaction forces were compared between the symptomatic FAI, asymptomatic FAI and non-FAI populations during a 45˚ cross-body lunge.

2.2 Participants

Nine individuals with symptomatic FAI, thirteen individuals with asymptomatic FAI, and eleven individuals without FAI participated. The thirty-three total participants were recruited from the Investigations of Mobility, Physical Activity, and Knowledge Translation in Hip Pain (IMPAKT-HIP) study (Guo et al., 2018; Kopec et al., 2017).

Participants were recruited via phone contact by a research coordinator. During the phone call, the participants were screened for participation in the study by being asked questions regarding their eligibility in the study based on the inclusion and exclusion criteria defined below in Table 2.1 and Table 2.2, respectively. Furthermore, to classify participants as symptomatic or asymptomatic, the first question of screening inquired about upper thigh or groin pain over the past twelve months. If the participants reported that they had pain either lasting for six weeks or longer or that occurred three times or more, then they were termed symptomatic. If the participants did not meet these criteria, then they were termed asymptomatic. If deemed eligible, they were debriefed about the study protocol, and were instructed to view a study information form sent to them via email by the research coordinator prior to attending the data collection session.

Table 2.1: Inclusion criteria

Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls
• Between 20 and 60 years old • Diagnosed with FAI and presented with radiological FAI on X-ray radiographs • Reported upper thigh or groin pain on screening question asked at phone contact recruitment (having any pain in the upper thigh or groin that lasted for six weeks or more or that occurred three times or more)	• Between 20 and 60 years old • Diagnosed with FAI and presented with radiological FAI on X-ray radiographs	• Between 20 and 60 years old • Healthy (no self-reported upper thigh or groin pain)

Table 2.2: Exclusion criteria

Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls
• Previous lower limb surgeries that currently affected one's every-day, recreational or sporting activities (where currently meant over the past 12 months) • History of lower body injuries which included hip or thigh, and/or knee or lower leg, and/or ankle or foot that currently affected one's every-day, recreational or sporting activities for at least a month (where currently meant over the past 12 months) • History of any inflammatory or autoimmune diseases • History of avascular necrosis of the hip • Diagnosed osteoarthritis of the hip, knee and ankle • History of any neurological conditions that affected lower limb physical function over the past 12 months	• Previous lower limb surgeries that currently affected one's every-day, recreational or sporting activities (where currently meant over the past 12 months) • History of lower body injuries which included hip or thigh, and/or knee or lower leg, and/or ankle or foot that currently affected one's every-day, recreational or sporting activities for at least a month (where currently meant over the past 12 months) • History of any inflammatory or autoimmune diseases • History of avascular necrosis of the hip • Diagnosed osteoarthritis of the hip, knee and ankle • History of any neurological conditions that affected lower limb physical function over the past 12 months	• Previous lower limb surgeries that currently affected one's every-day, recreational or sporting activities (where currently meant over the past 12 months) • History of lower body injuries which included hip or thigh, and/or knee or lower leg, and/or ankle or foot that currently affected one's every-day, recreational or sporting activities for at least a month (where currently meant over the past 12 months) • History of any inflammatory or autoimmune diseases • History of avascular necrosis of the hip • Diagnosed osteoarthritis of the hip, knee and ankle • History of any neurological conditions that affected lower limb physical function over the past 12 months

Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls
• Planned or previous lower limb joint replacement • BMI>35 kg/m^2	• Planned or previous lower limb joint replacement • BMI>35 kg/m^2 • Reported upper thigh or groin pain on screening question asked at phone contact recruitment	• Planned or previous lower limb joint replacement • BMI>35 kg/m^2 • Reported upper thigh or groin pain on screening question asked at phone contact recruitment • Presented with radiological FAI on X-ray radiographs

2.3 Data Collection

Participants attended a single, 1.5-hour testing session in the Motion Analysis and Biofeedback Laboratory at UBC Hospital. Upon entering the lab, the participants were first debriefed by the researcher regarding the study protocol and then signed the consent form. The data collection session was comprised of: the Copenhagen Hip and Groin Outcome Score (HAGOS), questions regarding sport participation, passive range of motion (ROM) testing, motion analysis while the participant performed a 45˚ cross-body lunge, and questions regarding self-reported pain in various joints and other body areas after lunging. For the purposes of testing, the study hip was defined at initial recruitment in the IMPAKT-HIP study as follows: if radiographic FAI was present in both hips, the study hip was the most symptomatic side; if there was no pain or equal amount of pain in both hips, then the study hip was randomized (Guo et al., 2018).

2.3.1 The Copenhagen Hip and Groin Outcome Score (HAGOS)

The Copenhagen Hip and Groin Outcome Score (HAGOS) was provided to each participant and was completed for their study hip only. The HAGOS quantifies one's view on their hip and/or groin during the past week and has 37 questions. There are 5 questions regarding symptoms, 2 questions on stiffness, 10 questions asking about pain, 5 questions about physical function and daily living, 8 questions about function, sports and recreational activities, 2 questions regarding participation in physical activities and 5 questions about quality of life (Thorborg et al., 2011). According to the 2016 Warwick Agreement on femoroacetabular impingement syndrome, the HAGOS is a recommended questionnaire to characterize adults with hip joint pain (Griffin et al., 2016). It was developed using the COnsensus-based Standards for the selection of health Measurement Instruments (COSMIN) checklist and has good content validity, construct validity and test-retest reliability (intraclass correlation coefficients ranged from 0.82-0.91 for all six subscales) (Thorborg et al., 2011). The HAGOS was used to quantify physical function and to help explain differences in lunge performance between the three groups.

2.3.2 Sport Participation

Because of the known prevalence of FAI in the athletic population (as mentioned in section 1.4.2), information regarding sport participation in the past month was gathered. More specifically, participants were asked to report the number of sports played, the frequency of sport participation per week (0x/week, 1-2x/week, 3-5x/week and 6-7x/week) and the level of play (whether recreational or competitive). Competitive athletes were operationally defined as: athletes belonging to sports teams or clubs, or school teams and who participated in sports at a competitive level (Yeung et al., 1994), and/or who were competing in international sports events.

Since the level of play was either recreational or competitive, any participant that did not participate in competitive sports was considered a recreational athlete.

Similar to a previous study (Lewis et al., 2018b), sport participation in this study was documented to further describe and differentiate between the symptomatic FAI, asymptomatic FAI and control groups. It was also documented to help explain certain biomechanical differences between participants, as certain variables like hip flexion (an important variable in this study) have shown to be statistically significantly different between athletes of different levels of play while lunging (Mei et al., 2017).

2.3.3 Hip Range of Motion Assessment

Passive hip range of motion (ROM) was assessed on the study hip using a handheld goniometer for the following hip movements: flexion, extension, abduction, adduction, internal rotation and external rotation. Flexion, abduction and adduction were measured with the participants in supine and a belt fixed around their anterior superior iliac spines. Extension, internal rotation and external rotation were measured in prone with the belt fixed around their posterior superior iliac spines. As seen in Norkin and White (2016), the protocols were followed for all movements, except for one change to hip adduction, where the non-study leg was hanging off the side of the examination table (as opposed to laying on the examination table) to not constrain the movement of the study leg (Nussbaumer et al., 2010).

For each of the movements, the researcher brought the participant's hip into terminal ROM and/or until the participant expressed pain and/or discomfort. Once the end position was reached (as seen in Figures 2.1, 2.2 and 2.3), the researcher recorded the angle in degrees (°) from the goniometer. Each movement was performed three times, and the mean ROM was calculated from these three measurements (Nussbaumer et al., 2010). Furthermore, after the three measurements were recorded for each movement, pain and discomfort during the movement was quantified using separate 11-point numerical rating scales (NRS), one for pain and one for discomfort. Pain was described as experiencing an extremely unpleasant sensation or severe discomfort that had the potential for injury (Kumar and Elavarasi, 2016) if the study limb was brought further into the ROM. Discomfort was described as experiencing an unpleasant or uncomfortable non-painful sensation (Stanghellini, 2001) that did not have potential for injury if the study limb was brought further into the ROM. These scales ranged from 0 where zero represented no pain or discomfort, to 10 where ten represented maximal pain or discomfort. This scale is a valid and reliable measure used in research and clinical practice (Williamson and Hoggart, 2005).

The goniometer is a valid and reliable tool to measure hip ROM in the clinic (Gajdosik and Bohannon, 1987). More specifically, the assessment of passive hip ROM can be performed using a goniometer as it is reliable and valid in healthy (Roach et al., 2013) and clinical (Nussbaumer et al., 2010; Pua et al., 2008) populations. With respect to the clinical populations, there is good to excellent intra-rater test-retest reliability for both individuals with hip osteoarthritis (Pua et al., 2008) and FAI (Nussbaumer et al., 2010), and good construct validity for people with FAI (Nussbaumer et al., 2010).

Hip ROM was assessed for this study to document values for all three populations and to use differences in ROM between populations as possible explanations for differences seen in performing the 45˚ cross-body lunge.

Figure 2.1: Passive hip flexion and hip extension ROM measurements. The end positions of hip flexion (left) and hip extension (right). A second assessor assisted with the hip extension measurement because overpressure needed to be applied to the study limb to reach the end position. This is not shown in the picture to better see the placement of the goniometer.

Figure 2.2: Passive hip adduction and hip abduction ROM measurements. The end positions for hip adduction (left) and hip abduction (right).

Figure 2.3: Passive hip internal rotation and hip external rotation ROM measurements. The end positions for hip internal rotation (left) and hip external rotation (right).

2.3.4 Motion Analysis

2.3.4.1 Instrumentation

Three-dimensional kinematics of the 45˚ cross-body lunge were collected at 120 Hertz (Hz) using a fourteen-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA). Kinetic data were derived from ground reaction forces collected from two force platforms (AMTI, Watertown, MA) sampled at 1200Hz. Fifty passive retroreflective markers were applied to various boney landmarks on the participant similar to the marker set utilized by Hammond and colleagues (2017). Bilateral markers were applied to the acromioclavicular joint, posterior superior iliac spine (PSIS), iliac crest, anterior superior iliac spine (ASIS), greater trochanter of femur, anterior thigh, lateral femoral epicondyle, medial femoral epicondyle, anterior shank, lateral malleolus, medial malleolus, posterior calcaneus, medial aspect of the head of the 1st metatarsal bone, dorsal aspect of the head of the 2nd metatarsal bone, and the lateral aspect of the head of the 5th metatarsal bone. Markers were also placed on vertebra C7, vertebra T10, right scapula, and sternal notch. Finally, bilateral shank plate clusters (4 markers on each shank), and bilateral thigh plate clusters (4 markers on each thigh) were applied to track the movement of their respective segments while performing the lunge. The marker placement can be seen in Figure 2.4.

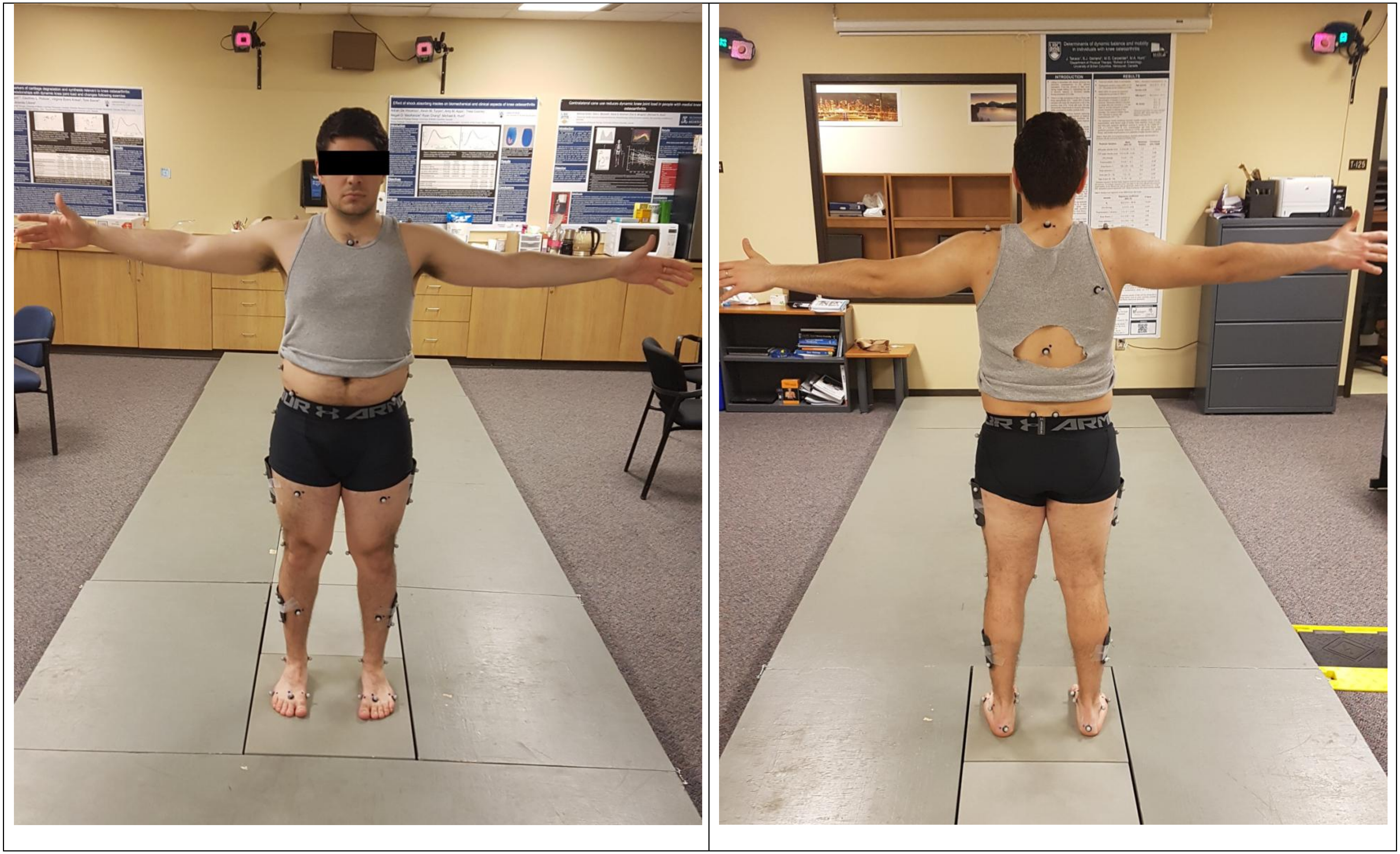

Figure 2.4: Marker placement.

2.3.4.2 Post Marker Placement

After the marker placement was completed, anthropometric measures were recorded. These measures included height, as well as bilateral foot length, foot width, knee diameter, and ankle diameter.

With all fifty markers, a static calibration trial was conducted prior to movement analysis to determine joint angle references, identify joint segments and orientations, and measure the mass of the participant. Each static calibration trial was conducted where the participant stood on a force platform in the anatomical position, with the arms abducted to the side. The mass of the participant was calculated from the force measurement obtained during the calibration trial. Once the calibration trial was complete, the two medial malleoli and two femoral epicondyle markers were removed for the dynamic trials.

After conducting the static calibration trial, participants were allowed to practice the lunge and determine a lunge distance that was repeatable. The participant was told to find a lunge distance that was long but comfortable, as the goal was to induce high amounts of hip flexion, without altering balance during the movement.

2.3.4.3 Lunge Procedures

For the lunge protocol, the participants performed a 45˚ cross-body lunge with the ‘study hip’ as the lead hip. The starting position involved the participant standing with their feet at roughly a 45˚ angle to an imaginary horizontal line passing through the force platforms and about hip to shoulder-width apart (Farrokhi et al., 2008), and their arms across their chest (Comfort et al., 2015). The starting position in the anterior view and the feet positioning can be seen in Figure 2.5.

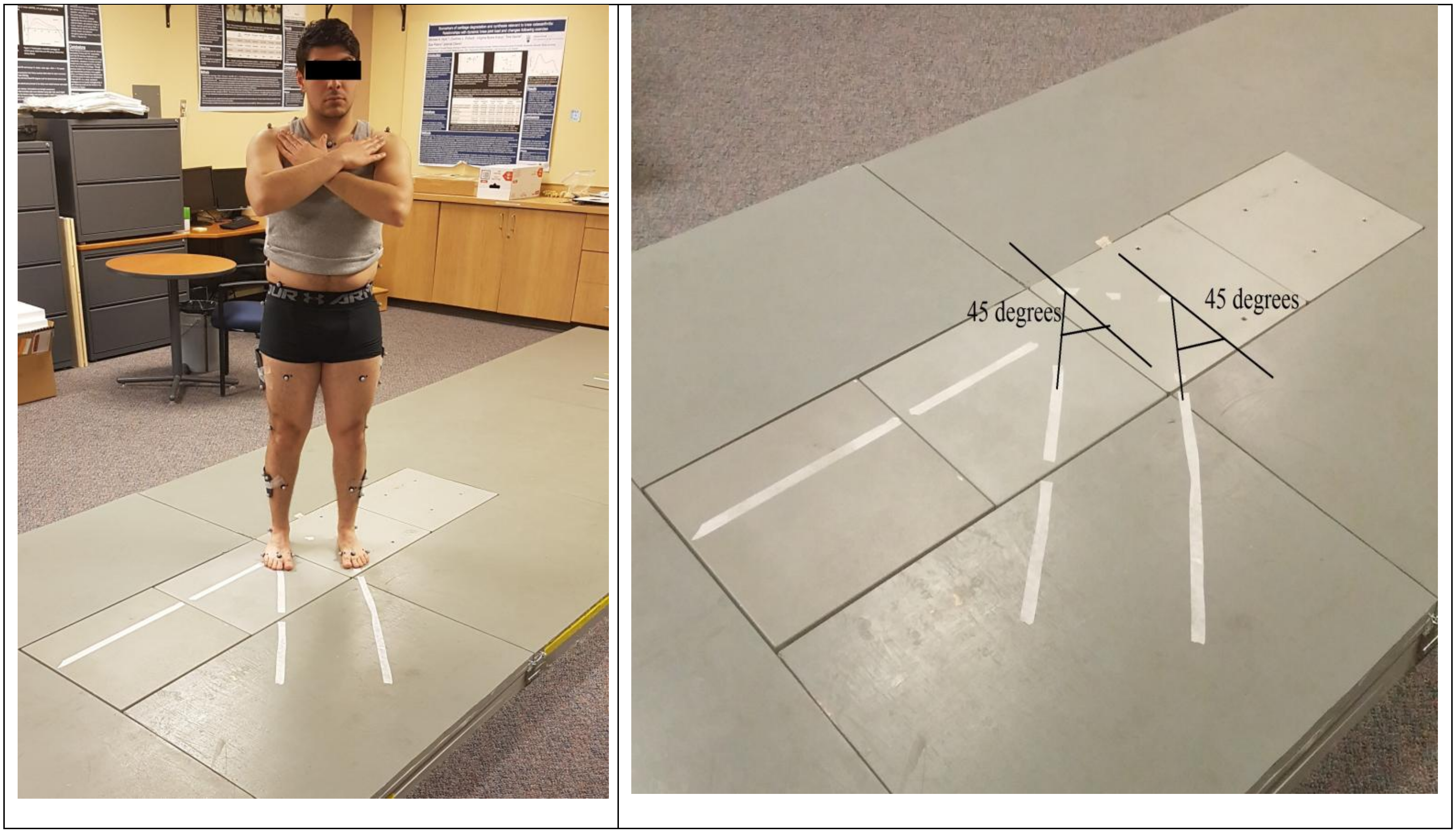

Figure 2.5: Anterior view of the 45˚ cross-body lunge starting position. The starting position for the 45˚ cross-body lunge (left) and the angulation and placement of the feet (right).

The distance between the feet was adjusted for every participant as each participant selected their own hip to shoulder width distance. This was done by placing tape behind each of their feet. This tape placement also served another purpose in that it allowed for the participants to start from the same position for every trial. This is seen in Figure 2.6 with the posterior view of the starting position and a close-up view of the tape placement just behind the feet.

Figure 2.6: Posterior view of the 45˚ cross-body lunge starting position. The starting position of the 45˚ cross-body lunge from the posterior view (left) and a close-up view of the tape placement just behind the feet (right).

Another piece of tape was placed roughly halfway between the two pieces of tape that were just behind the feet, and this can also be seen in Figure 2.6. This 'middle' tape helped estimate the centre of the pelvis and was a reference point for the goniometer to determine the 45˚ angle that the participants were lunging along. The stationary arm of the goniometer was parallel to the angulation of the feet, and the movable arm of the goniometer indicated the 45˚ line of path (with respect to the stationary arm of the goniometer), which was extended by placing tape down on the force platforms. Once the 45˚ angle was determined from the goniometer, it was removed from the ground to begin the lunge trials. The positioning of the goniometer and tape placement on the force platforms can be seen in Figure 2.7.

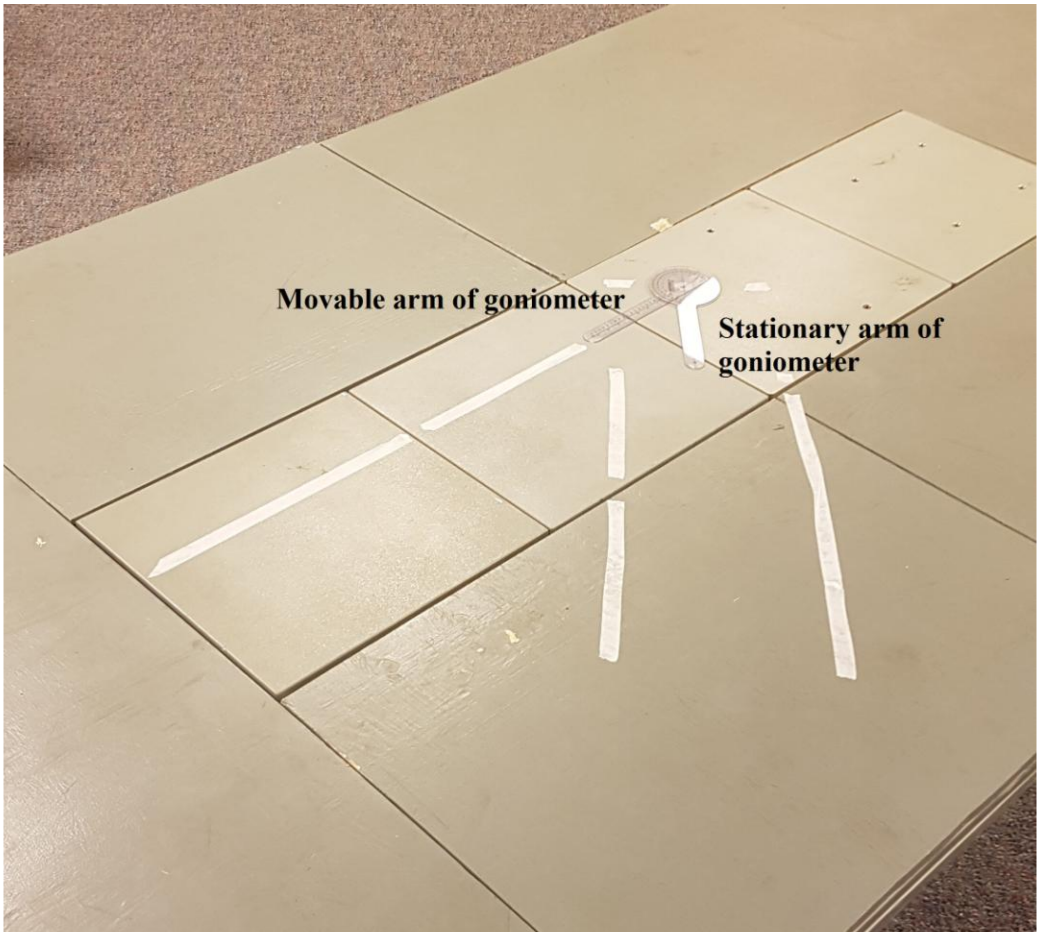

Figure 2.7: Goniometer and force platform tape placement. The tape placement on the force platforms, acting as an extension of the movable arm of the goniometer, indicated the 45˚ line of path.

Once the participant was in the starting position of the lunge, a count-down was initiated. The researcher asked if the participant was ready, and if ready, the researcher then said ‘Ready, Set, Go’. On the word ‘Set’, data recording started, and on the word ‘Go’, the participant initiated the lunge. To initiate the lunge, the participant swung their leg forward and across their body and landed on the force platform with their trunk and hips facing the direction of travel. The back foot remained facing the same direction as in the starting position and thus was not pivoted in the direction of movement (Houck, 2003). This was done to mimic a crossover step or lunge performed in a sport situation (Roetert and Kovacs, 2011), and induced more hip adduction than with the back foot pivoting (based on pilot data). The lunge position and the placement of the non-pivoted back foot can be seen in Figure 2.8. Once the maximal lunge depth was achieved, the participant was told to push off the force platform and return to the initial starting position. After each repetition, there was a brief rest period to give the participant enough time to regain any balance and to start from the same position as the repetition before.

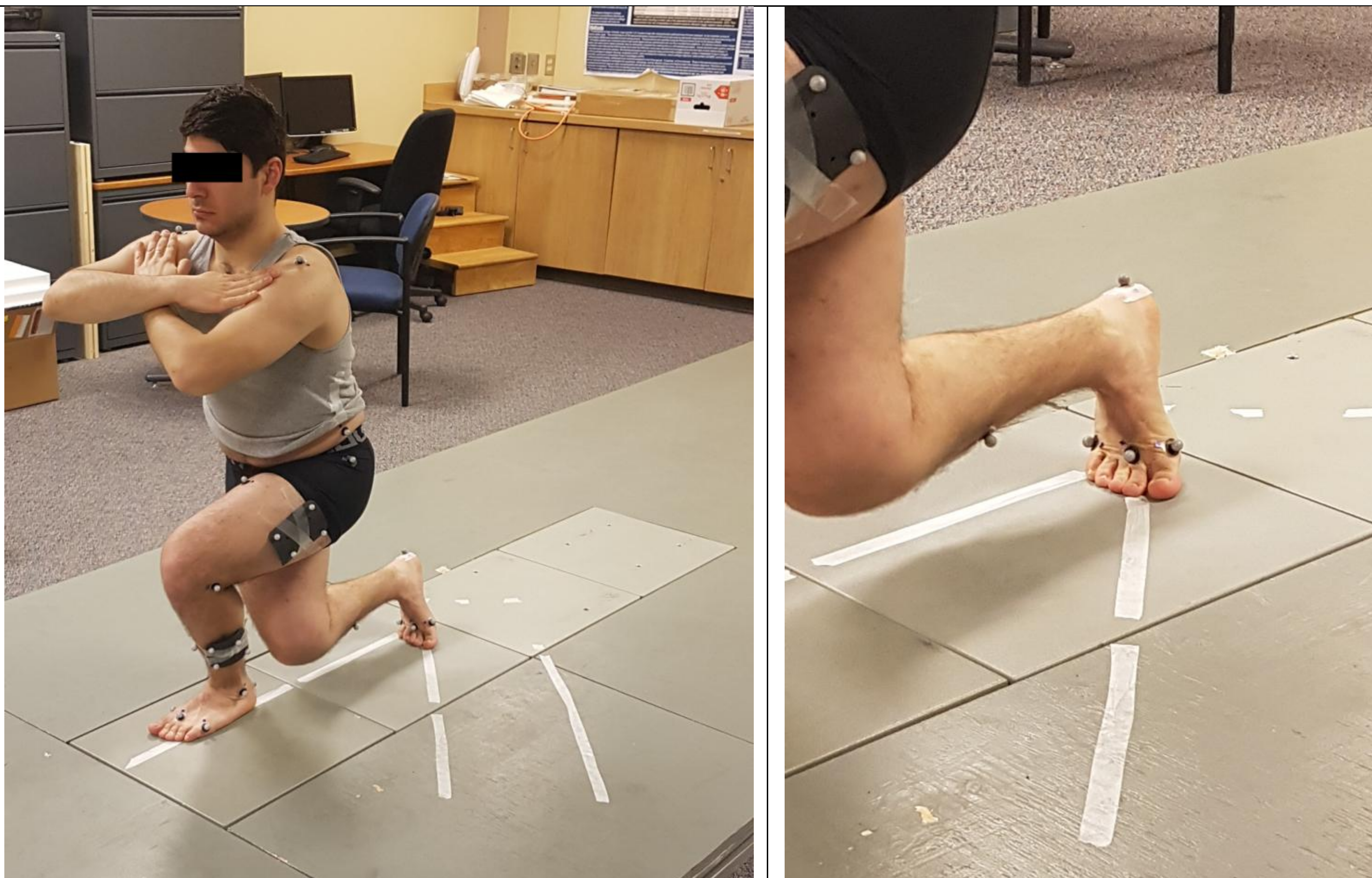

Figure 2.8: 45˚ cross-body lunge at maximal lunge depth. Peak knee flexion of lead limb or maximal lunge depth of the 45˚ cross-body lunge (left) and the positioning of the non-pivoted back foot (right).

For all trials, the participants were asked to lunge as naturally as possible, at their self-selected speed, distance and depth. Seven adequate lunge trials were performed by each participant. The lunge was deemed adequate if: 1) the knee of the trail leg did not contact the ground, 2) the lead foot stayed completely flat on the ground, 3) the participant was not visibly off-balance or had a subjective feeling of being off-balance (Farrokhi et al., 2008; Schütz et al., 2014) and 4) the back foot did not pivot. In addition, the lunge was acceptable if the lead leg and feet, hips and trunk were facing the direction of travel, as seen in Figure 2.8. No instruction of trunk placement or front knee displacement was provided while performing the lunges as these variables play a role in differences in joint kinematics and kinetics while performing the lunge (Farrokhi et al., 2008; Hofmann et al., 2017; Schütz et al., 2014).

After all trials were completed, the participants were asked to rate the amount of hip and groin pain experienced on an 11-point numerical rating scale (NRS) from 0-10, where zero is no pain and 10 is the maximal amount of pain. In addition to hip and groin pain, the presence of pain in other joints like the knee and ankle joints, and other areas of the body like lower back, was ascertained, as was whether the lunge movements reproduced the pain one experiences on a daily basis. Answers to the last question included ‘yes’, ‘no’, ‘not applicable’ and ‘unsure’ options and, if needed, explanations were indicated on the data collection form. The ‘unsure’ option was provided because seven participants with symptomatic acetabular labral tears in the paper by Dwyer and colleagues (2016) described their pain during the lunge as uncomfortable and could not confidently give a rating for pain.

2.4 Data Analysis

The data analysis involved two time frames. The first time frame occurred while the lead foot was in contact with the force platform, where the start and end points of this time frame were ‘force platform on’ and ‘force platform off’, respectively. ‘Force platform on’ was defined as the vGRF achieving a threshold value of ≥20N, and ‘force platform off’ was defined as the vGRF achieving a threshold value of ≤20N (Comfort et al., 2015). The second time frame involved the entire 45˚ cross-body lunge movement (from starting position, lunging onto the force platform and returning to starting position). The start and end points of the entire 45˚ cross-body lunge movement were determined using the position of the lead limb’s heel marker in the +Z direction. Between the time when the researcher said ‘Set’ and ‘Go’, multiple frames of the static positions of all markers in all three directions (X, Y and Z) were recorded while the participant was in the starting position (as seen in Figure 2.5). When the lead limb was lifted off the ground to initiate the lunge, the ‘start of lunge’ was defined as the lead limb’s heel marker reaching a position that was 1.75 times higher than its position in the starting position (as seen in Figure 2.5). Similarly, when the lead limb was brought back to the starting position to complete the lunge, the ‘end of lunge’ was defined as the lead limb’s heel marker reaching a position that was 1.75 times higher than its position in the starting position (as seen in Figure 2.5). Kinematic analysis occurred during the entire lunge movement and kinetic analysis occurred during force platform contact.

2.4.1 Kinematic Data

Three-dimensional marker trajectories were processed and filtered using a fourth order low pass 6Hz Butterworth filter in Cortex 5.3 (Motion Analysis Corporation, Santa Rosa, CA) and exported to Visual 3D (C-Motion Inc, Rockville, MD) for calculation of hip, pelvis, knee, ankle, and trunk angles. The segments involved with the calculation of these angles will be discussed below, which includes the markers that defined each segment, and the segment origins and axes determination.

2.4.1.1 Pelvis

The pelvis was defined using the two ASIS markers and the two PSIS markers, and the movement of the pelvis was also tracked by the ASIS markers, PSIS markers and the iliac crest markers. As seen in previous studies (Comfort et al., 2015; Lewis et al., 2018b), the Coda Pelvis was used because markers were applied to both the ASIS and PSIS, and these landmarks were palpable on the participants. The origin of the pelvis' coordinate system was halfway between the two ASIS markers, where the anterior-posterior axis was oriented towards the point midway between the bilateral PSIS markers; the medial-lateral axis was orthogonal to the plane defined by the bilateral ASIS markers and origin of the pelvis' coordinate system; and the vertical axis was orthogonal to the other two axes (Robertson et al., 2013).

2.4.1.2 Thigh

The thigh segment was defined using the medial and lateral femoral epicondyles, ASIS, and the hip joint centre, and the movement of the thigh was tracked using the rigid plates placed on the lateral aspect of the thigh (as mentioned in section 2.3.4.1). The hip joint centre was estimated from regression equations using the inter-ASIS distance (Bell et al., 1989; Bell et al., 1990), and was automatically generated in Visual 3D when the Coda Pelvis was created. The origin of the thigh's coordinate system was at the hip joint centre, where the vertical axis was oriented towards the point midway between the medial and lateral femoral epicondyles; the anterior-posterior axis was orthogonal to the plane defined by the medial and lateral femoral epicondyles, ASIS and hip joint centre; and the medial-lateral axis was orthogonal to the other two axes (Robertson et al., 2013).

2.4.1.3 Shank

The shank segment was defined using the medial and lateral malleoli and the medial and lateral femoral epicondyles, and the movement of the shank was tracked using the rigid plates placed on the lateral aspect of the shank (as mentioned in section 2.3.4.1). The origin of the shank's coordinate system was halfway between the medial and lateral femoral epicondyles, where the vertical axis was oriented towards the point midway between the medial and lateral malleoli; the anterior-posterior axis was orthogonal to the plane defined by the medial and lateral femoral epicondyles and malleoli; and the medial-lateral axis was orthogonal to the other two axes (Robertson et al., 2013).

2.4.1.4 Foot

The foot segment was defined using the medial and lateral malleoli and the 2nd metatarsal head, and the movement of the foot was tracked using the 2nd metatarsal head, 1st metatarsal head and 5th metatarsal head markers of their respective bones, and the heel marker. The origin of the foot's coordinate system was halfway between the medial and lateral malleoli, where the anterior-posterior axis was oriented towards the midpoint of the foot width; the medial-lateral axis was passing through the medial and lateral malleoli; and the vertical axis was orthogonal to the other two axes (Robertson et al., 2013).

2.4.1.5 Trunk

The trunk segment was defined using the bilateral iliac crest markers and the bilateral acromioclavicular joint markers, and the movement of this segment was tracked using the C7, T10 and the sternal notch markers. The origin of the trunk's coordinate system was located midway between the two iliac crest markers, where the vertical axis was oriented towards the point midway between the bilateral acromioclavicular markers; the medial-lateral axis was oriented towards the right iliac crest marker; and the anterior-posterior axis was orthogonal to the other two axes (Robertson et al., 2013).

2.4.1.6 General Kinematic Model Parameters

To calculate the position and orientation of the segments (based on their definitions as previously mentioned) by tracking their coordinate systems, an inverse kinematics (IK) model was constructed (Hale et al., 2014). This IK approach, also called global optimization (Lu and O'Connor, 1999), applied constraints to the joints formed from the positions of the segments in the static trial to help minimize the effect of soft tissue artifact in the dynamic lunge trials. The constraints that were applied to the joints refer to restrictions in the degrees of freedom of the joint, whereby degrees of freedom is the ability of the segments (composing the joint) to undergo translation and rotation in all three planes. The pelvis segment was optimized for translation and rotation in all three planes, whereas the thigh, shank, foot and trunk segments' tri-planar translations were minimized but tri-planar rotations were allowed. Soft tissue artifact is a common source of motion analysis error and is the movement of the skin-attached marker relative to the underlying bone (Robertson et al., 2013). Because this can potentially lead to errors in tracking positions and orientations of segments, and ultimately calculations of biomechanical variables, it was important to attempt to minimize this effect.

2.4.1.7 Joint Angle Calculations

The hip, knee and ankle joint angles were determined using the local joint coordinate system which involved the segment coordinate systems that were previously mentioned in sections 2.4.1.1 to 2.4.1.5 above. In the local joint coordinate system, the relative joint angle was calculated from the orientations of the proximal and distal segments using Cardan XYZ sequences of rotation (Grood and Suntay, 1983). The pelvis and trunk angles were also calculated using Cardan XYZ sequences of rotation, but were calculated relative to the global coordinate system (Bagwell et al., 2016). Ensemble average curves were graphed for all kinematic variables from ‘start of lunge’ to ‘end of lunge’.

2.4.1.8 Kinematic Variables

Kinematic outcome measures included: sagittal, frontal and transverse plane hip angles at maximum lunge depth (defined as peak knee flexion in the lead knee), sagittal plane knee angle at maximum lunge depth, and sagittal plane ankle angle at maximum lunge depth. Pelvis excursion in the sagittal, frontal and transverse planes throughout the entire movement, and sagittal plane trunk angle (forward trunk lean) at maximum lunge depth were also analyzed and compared between groups. The value for each discrete kinematic variable was computed from taking an average of the calculated variables for five of the seven lunge trials. For each participant (apart from two control participants) the five trials that produced the lowest coefficient of variation for all kinematic variables were chosen for analysis. For two control participants, the four trials that produced the lowest coefficient of variation for the hip transverse plane angle at peak knee flexion was used instead as there were unrelated data processing issues beyond our control.

2.4.2 Kinetic Data

Initially, the ground reaction force (GRF) data while lunging were exported from Cortex to Visual3D. An inverse dynamics approach was used to calculate internal joint moments about the hip, knee and ankle based upon the kinematics of the model produced and the ground reaction forces applied to the body during the 45˚ cross-body lunge. The internal joint moments were then filtered using a second order 6Hz low pass Butterworth filter within Visual3D, and expressed as external joint moments for the purpose of analysis as seen in previous studies (Comfort et al., 2015; Diamond et al., 2018; Diamond et al., 2017; Diamond et al., 2016; Hammond et al., 2017; Hunt et al., 2013). Ensemble average curves were constructed from 'force platform on' to 'force platform off" for the external joint moments and vGRFs. The mathematical integral under the ensemble average curves for the external joint moments, taking into account positive and negative values, represented the joint moment net impulses (Farrokhi et al., 2008; Flanagan et al., 2004; Riemann et al., 2013; Riemann et al., 2012). All joint moment and joint moment net impulse data were normalized to %body weight*height (%BW*Ht) and the vGRFs were normalized to body weight (BW).

2.4.2.1 Kinetic Variables

Kinetic variables included: peak external hip moments and hip joint moment net impulses in the sagittal, frontal and transverse planes, peak external knee moment and knee joint moment net impulse in the sagittal plane, and peak external ankle moment and ankle joint moment net impulse in the sagittal plane. The lead limb's maximal vGRF and trail limb's minimal vGRF during lunge descent (between the time from 'force platform on' to peak lead knee flexion), and lunge ascent (between the time from peak lead knee flexion to 'force platform off') were identified. Similar to the kinematic variables, the value for each discrete kinetic variable was computed from taking an average of the calculated variables for five trials.

2.4.3 Spatiotemporal Variables

The spatiotemporal variables included lunge distance, maximum lunge depth, and contact time with the force platform, and were also compared across groups. Because the lunge was performed at a 45˚ angle, the lunge distance was the linear displacement (m) of the marker on the head of the 2nd metatarsal bone from the 45˚ cross-body lunge starting position to 'force platform on'. The lunge distance was then normalized to leg length, which was calculated as the distance (m) from the ASIS marker of the study limb to the medial malleoli marker of the study limb (Dwyer et al., 2010). Maximum lunge depth was defined as the peak knee flexion angle (°) for the lead limb while performing the lunge. As seen in previous studies (Dwyer et al., 2016; Longpré et al., 2015), knee flexion has been used as a proxy for lunge depth. Contact time with the force platform was defined as the amount of time (sec) from 'force platform on' to 'force platform off'.

A list of all outcome measures is shown in Table 2.3.

Table 2.3: List of outcome measures.

Category	Outcome (units)
Kinematics	Hip Joint • Sagittal plane angle at maximum lunge depth (°) • Frontal plane angle at maximum lunge depth (°) • Transverse plane angle at maximum lunge depth (°) Pelvis • Excursion in sagittal plane (°) • Excursion in frontal plane (°) • Excursion in transverse plane (°) Knee Joint • Sagittal plane angle at maximum lunge depth (°) Ankle Joint • Sagittal plane angle at maximum lunge depth (°) Trunk • Sagittal plane angle at maximum lunge depth (°)
Kinetics	Hip Joint • Peak external sagittal plane moment (%BW*Ht) • Peak external frontal plane moment (%BW*Ht) • Sagittal plane joint moment net impulse [s*(%BW*Ht)] • Frontal plane joint moment net impulse [s*(%BW*Ht)] Knee Joint • Peak external sagittal plane moment (%BW*Ht) • Sagittal plane joint moment net impulse [s*(%BW*Ht)] Ankle Joint • Peak external sagittal plane moment (%BW*Ht) • Sagittal plane joint moment net impulse [s*(%BW*Ht)]

Category	Outcome (units)
	Vertical Ground Reaction Forces (vGRF) • Maximum lead limb vGRF during lunge descent (BW) • Maximum lead limb vGRF during lunge ascent (BW) • Minimum trail limb vGRF during lunge descent (BW) • Minimum trail limb vGRF during lunge ascent (BW)
Spatiotemporal	Contact time with force platform (sec) Lunge distance (% leg length) Maximum lunge depth (°)

2.4.4 Sample Size

A sample size calculation was not done because of this study being exploratory in nature (Jones et al., 2003). However, a sample size goal of 10 participants in each group (total of 30 participants) was chosen as a previous study found statistically significant differences in peak hip flexion between three different squatting techniques in 28 healthy controls with nine participants in the first group, nine in the second group, and ten in the third group (Butler et al., 2010). As the study by Butler et al. (2010) still found statistically significant differences in hip flexion (an important variable in this current study) between three groups, statistically significant differences in this current study may be found with 10 participants in each group.

2.4.5 Statistical Analysis

Means and standard deviations were calculated for each group on the study limb only. All data (demographic, kinematic, kinetic, spatiotemporal and range of motion) were examined for normality and unequal variances using the Shapiro-Wilk statistic and the Levene’s test, respectively, prior to the omnibus test. Because of the relatively small sample size in this study, a conservative approach was used for outlier detection, where outliers were removed if they met two criteria: a) falling outside 1.5 times the interquartile range above and below the 75^{th} and 25^{th} quartile values for each variable (Rousseeuw and Hubert, 2011) and b) achieving a Z score either greater than 2.5 or less than -2.5 for each variable (Rousseeuw and Hubert, 2011). Specifically, if the mean value across the five trials for a given participant was deemed to be an outlier based on these criteria, the data for that participant was removed for that variable only. One-way analyses of variances (ANOVA's) were conducted to test between-group comparisons on demographic, biomechanical, spatiotemporal and range of motion outcome measures. A chi-square Fisher's exact test was also used to determine if there were between-group differences in sex distribution. If the omnibus tests were significant, using a p value <0.05, then post hoc Tukey-Kramer tests were run to determine where the differences lie. Welch's ANOVA was used as an omnibus test (p value <0.05) and Games-Howell was used as a post-hoc test if the assumption of homogeneity of variance was violated. All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS v. 23; IBM Corp., Armonk, NY).

Chapter 3: Results

3.1 Participant Demographics

Participant demographic data are reported in Table 3.1. Age (p=0.571), height (p=0.371), body mass (p=0.072), BMI (p=0.198) and sex distribution (p=0.633) were not statistically significant among the three groups. In terms of FAI morphologies that were present, the sFAI group had two individuals with cam, five with pincer, and two with mixed, and the aFAI group had four individuals with cam, six with pincer, and three with mixed. Radiographic evidence of FAI was found more bilaterally than unilaterally in both the sFAI group (6 bilateral participants and 3 unilateral participants) and aFAI group (11 bilateral participants and 2 participants). Of the nine participants with symptomatic FAI, symptoms were present bilaterally in 4 participants and unilaterally in 5 participants. Moreover, those in the sFAI group reported symptom durations for an average of 179.4 months prior to testing.

Table 3.1: Demographic data. Values are reported as mean (sd), unless otherwise noted.

Outcome	**Symptomatic FAI (n=9)**	**Asymptomatic FAI (n=13)**	**Asymptomatic Controls (n=11)**	**p value**
Age (years)	50.7 (3.6)	48.2 (7.3)	47.7 (7.3)	0.571
Height (cm)	167.5 (15.3)	173.4 (7.5)	168.1 (12.9)	0.371
Body mass (kg)	68.6 (18.1)	80.1 (13.6)	67.5 (11.2)	0.072
BMI (kg/m^2)	24.2 (4.5)	26.6 (4.1)	23.9 (3.2)	0.198
Sex (male:female)	3:6	5:8	2:9	0.633
Dominant leg (right:left)	8:1	11:2	10:1	
Study hip (right:left)	6:3	6:7	6:5	
FAI morphology (cam:pincer:mixed)	2:5:2	4:6:3	N/A	
FAI laterality (unilateral:bilateral)	3:6	2:11	N/A	
Symptoms laterality (unilateral:bilateral)	5:4	N/A	N/A	

Results are considered significant if $p<0.05$.

Individuals in this study also participated in a wide range of sporting activities over the past month. For the symptomatic FAI group, most of the participation was non-competitive, the most common activities were running and walking, and other activities included basketball, ice hockey, swimming, biking, pickleball and aerobics/weight class. The frequency of sport participation ranged from 1-2x/week to 6-7x/week. Like the sFAI group, most of the participation for the aFAI group was non-competitive. The most common activities were walking, hiking, biking and running, and other activities included swimming, floor hockey, ice hockey, tennis, weight training, skiing, kayaking, boot camp, yoga and pilates. The frequency of sport participation ranged from 1-2x/week to 6-7x/week. Finally, all sport participation in the control group was non-competitive. The most common activities were walking, running and hiking, and other activities included biking, swimming, ice hockey, canoeing, paddleboarding, yoga, barre fitness class, aquasize class, pilates, aerobics and weight/cardio class. Like the sFAI and aFAI groups, the frequency of sport participation ranged from 1-2x/week to 6-7x/week.

3.2 Questionnaire data

Data from the Copenhagen Hip and Groin Outcome Score (HAGOS) subscales are listed in Table 3.2. The participants with sFAI exhibited statistically significantly lower scores on all HAGOS subscales compared to both the aFAI and control groups, and there were no statistically significant differences in the scores between the aFAI and control groups for all subscales.

Table 3.2: Questionnaire data. Values are reported as mean (sd), unless otherwise noted.

Subscale	Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls	p values
Symptoms and Stiffness*,‡	60.3 (20.8)	92.9 (4.8)	92.2 (11.5)	0.002
Pain*,‡	64.4 (24.2)	98.8 (1.9)	95.9 (6.4)	0.003
Physical function, daily living*,‡	68.9 (25.5)	98.1 (3.3)	95.9 (5.8)	0.013
Function, sports and recreational activities*,‡	60.8 (22.1)	96.2 (7.2)	95.5 (10.2)	0.001
Participation in physical activities*,‡	51.4 (28.9)	97.1 (7.5)	93.2 (10.3)	0.001
Quality of life*,‡	56.7 (27.7)	96.5 (5.9)	92.3 (16.8)	0.004

* indicates statistically significant differences between sFAI and aFAI.
‡ indicates statistically significant differences between sFAI and controls.
For all subscales of the HAGOS, the scores range from 0-100, where 0 indicates extreme problems and 100 indicates no problems.
Results are considered significant if $p<0.05$.

3.3 Passive Hip Range of Motion Data

Passive hip range of motion in all three planes, along with values for study hip pain and discomfort (as measured on the NRS), are listed in Table 3.3. The passive hip range of motion values for the sFAI participants are from only 8/9 participants as one sFAI participant had a considerable amount of pain after performing the 45° cross-body lunge. The participants with sFAI exhibited a statistically significantly smaller (p=0.009) passive hip abduction range of motion (31.8° ± 9.5°) compared to the control group (43.9° ± 9.3°), and the participants with aFAI exhibited a statistically significantly larger (p=0.012) passive hip extension range of motion (25.2° ± 5.8°) compared to the control group (18.8° ± 4.4°). Furthermore, the aFAI group exhibited statistically significantly less (p=0.043) passive hip flexion range of motion (107.1° ± 8.6°) compared to the control group (116.8° ± 9.4°). There were no other statistically significant between-group differences for the other passive hip range of motion variables.

The sFAI and aFAI groups reported study hip pain and discomfort during all six passive hip range of motion assessments, whereas the control group reported small amounts of study hip pain during passive hip flexion, abduction and internal rotation and discomfort during passive hip flexion, extension, abduction and internal rotation. Participants in the sFAI group also reported discomfort in other body areas, which included the lower back and thigh. Participants in the aFAI group also reported lower back, thigh and knee discomfort. Finally, participants in the control group also exhibited pain and discomfort in other body areas. These included thigh and lower back pain and thigh, groin, knee and lower back discomfort.

Table 3.3: Passive hip range of motion data. Values are reported as mean (sd), unless otherwise noted.

Outcome	Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls	p values
Flexion (°)†	103.0 (20.3)	107.1 (8.6)	116.8 (9.4)	0.046
Pain (0-10)	2.7 (3.6)	0.5 (1.1)	0.3 (0.6)	
Discomfort (0-10)	2.1 (3.1)	0.1 (0.3)	0.6 (1.3)	
Extension (°)†	23.8 (4.9)	25.2 (5.8)	18.8 (4.4)	0.014
Pain (0-10)	1.0 (2.6)	0.2 (0.8)	0.0 (0.0)	
Discomfort (0-10)	1.4 (2.3)	0.3 (0.6)	0.1 (0.3)	
Adduction (°)	22.1 (4.2)	23.1 (3.5)	22.9 (4.5)	0.850
Pain (0-10)	1.6 (2.7)	0.2 (0.6)	0.0 (0.0)	
Discomfort (0-10)	0.9 (1.5)	0.2 (0.6)	0.0 (0.0)	
Abduction (°)‡	31.8 (9.5)	36.7 (5.8)	43.9 (9.3)	0.010
Pain (0-10)	5.1 (3.3)	1.0 (1.6)	0.4 (1.2)	
Discomfort (0-10)	1.9 (3.3)	0.4 (0.8)	0.1 (0.3)	
Internal Rotation (°)	39.2 (8.8)	44.6 (9.4)	44.9 (6.7)	0.286
Pain (0-10)	2.1 (2.9)	0.5 (1.5)	0.2 (0.6)	
Discomfort (0-10)	0.9 (1.6)	0.2 (0.4)	0.2 (0.6)	
External Rotation (°)	43.0 (6.1)	44.1 (7.1)	45.3 (7.4)	0.781
Pain (0-10)	1.0 (2.2)	0.1 (0.3)	0.0 (0.0)	
Discomfort (0-10)	0.3 (0.5)	0.1 (0.3)	0.0 (0.0)	

† indicates statistically significant differences between aFAI and controls;
‡ indicates statistically significant differences between sFAI and controls;
Results are considered significant if $p<0.05$.

3.4 Spatiotemporal Outcomes

Spatiotemporal variables were compared across the three groups and are reported in Table 3.4. There were no statistically significant between-group differences for any spatiotemporal variable while performing the 45° cross-body lunge: contact time with the force platform (p=0.081), maximum lunge depth (p=0.679), or lunge distance (p=0.511).

Table 3.4: Spatiotemporal data. Values are reported as mean (sd), unless otherwise noted.

Outcome	Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls	p values
Contact time with force platform (sec)	3.37 (1.75)	2.49 (0.60)	2.03 (0.67)	0.081
Maximum lunge depth (° of lead knee flexion)	101.1 (14.4)	101.8 (10.7)	105.1 (8.4)	0.679
Lunge distance (% lead leg length)	104.7 (17.9)	110.8 (9.4)	106.5 (12.1)	0.511

Results are considered significant if $p<0.05$.

3.5 Kinematic Outcomes

Kinematic variables at peak knee flexion were compared across the three groups and their values are reported in Table 3.5. There were no statistically significant between-group differences for any kinematic variable examined at peak knee flexion while performing the 45° cross-body lunge: hip sagittal angle (p=0.538), hip frontal angle (p=0.296), hip transverse angle (p=0.406), ankle sagittal angle (p=0.195) or trunk sagittal angle (p=0.769). Group ensemble average curves are present in Figure 3.1 and Figure 3.2.

Pelvis kinematic outcomes were compared across the three groups and their values are reported in Table 3.6. One outlier was found for pelvis sagittal plane excursion in one of the aFAI participants. Thus, after removal, the pelvis sagittal plane excursion value in Table 3.6 is from twelve aFAI participants, instead of thirteen. The statistical analysis was performed before and after outlier removal, and before outlier removal, pelvis sagittal plane excursion was statistically significantly larger (p=0.046) in the sFAI group (26.6° ± 10.2) compared to the aFAI group (19.0° ± 4.8). However, after outlier removal, there were no longer any statistically significant between-group differences for this variable (p=0.074). Furthermore, there were no other statistically significant between-group differences for pelvis frontal plane excursion (p=0.358) or transverse plane excursion (p=0.602). The group ensemble average curve for pelvis motion is present in Figure 3.3.

Table 3.5: Kinematic data at peak knee flexion. Values are reported as mean (sd), unless otherwise noted.

Outcome	**Symptomatic FAI**	**Asymptomatic FAI**	**Asymptomatic controls**	**p values**
Hip sagittal angle (°)	105.9 (12.9)	100.8 (12.2)	100.8 (9.4)	0.538
Hip frontal angle (°)	14.0 (6.6)	11.8 (2.8)	14.3 (3.3)	0.296
Hip transverse angle (°)	-9.7 (10.1)	-4.3 (8.2)	-5.2 (10.3)	0.406
Ankle sagittal angle (°)	18.1 (4.7)	20.8 (6.3)	23.0 (6.3)	0.195
Trunk sagittal angle (°)	16.9 (14.9)	13.8 (9.0)	12.5 (10.9)	0.769

(+) values indicate hip flexion, adduction and internal rotation, knee flexion, ankle dorsiflexion, trunk forward flexion;
(-) values indicate hip extension, abduction and external rotation, knee extension, ankle plantarflexion, trunk extension;
Results are considered significant if p<0.05.

Table 3.6: Pelvis kinematic outcomes. Values are reported as mean (sd), unless otherwise noted.

Outcome	Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls	p values
Sagittal plane excursion (°)	26.6 (10.2)	17.9 (3.2)	20.0 (5.9)	0.074
Frontal plane excursion (°)	17.1 (6.2)	14.9 (3.4)	13.5 (4.1)	0.358
Transverse plane excursion (°)	48.9 (8.0)	51.4 (6.6)	48.8 (6.4)	0.602

(+) values indicate anterior pelvis tilt, contralateral side flexion of pelvis (relative to lead limb), contralateral rotation of pelvis (relative to lead limb);
(-) values indicate posterior pelvis tilt, ipsilateral side flexion of pelvis (relative to lead limb), ipsilateral rotation of pelvis (relative to lead limb);
Results are considered significant if $p<0.05$.

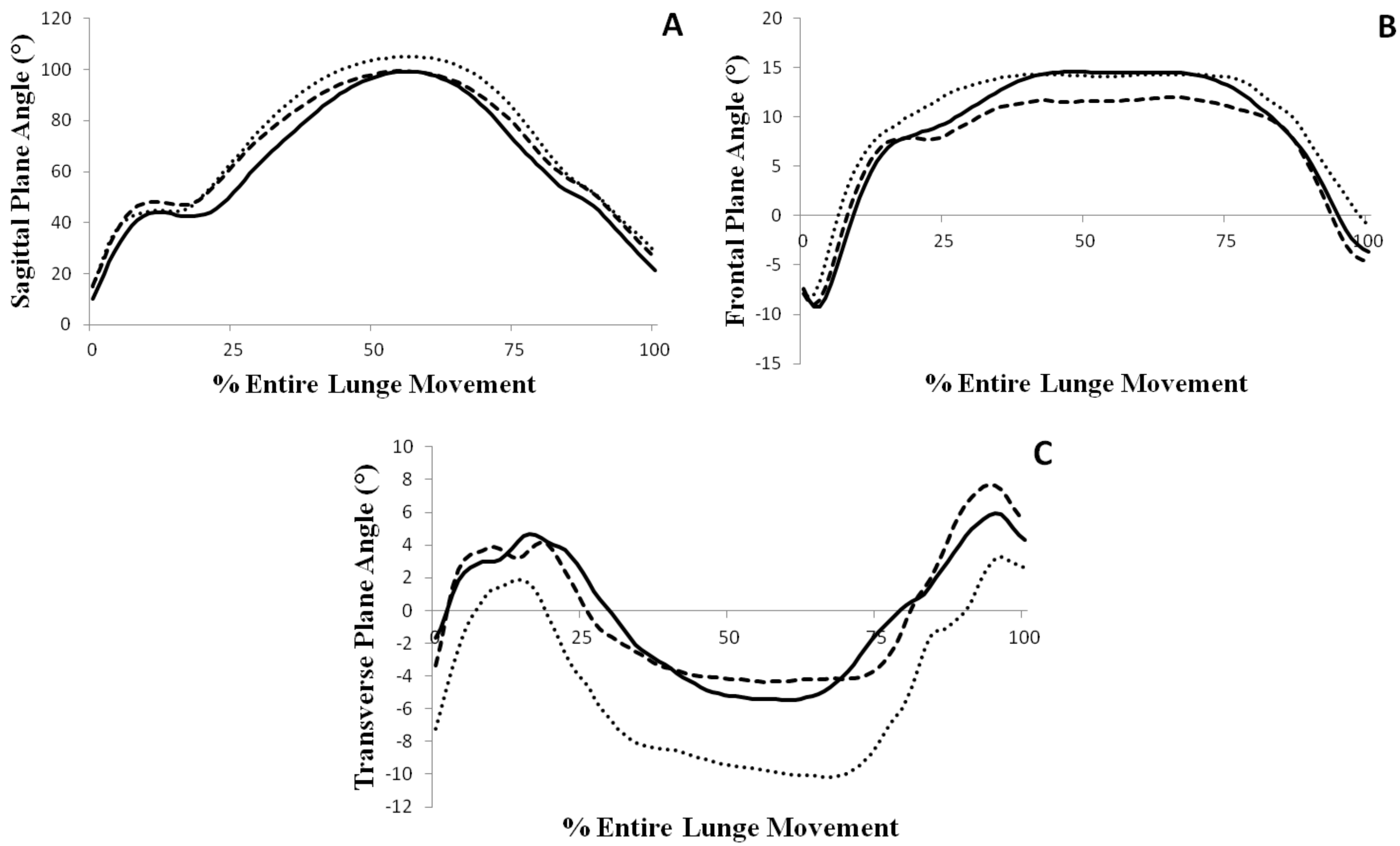

Figure 3.1: Kinematic ensemble averages of the hip in the sagittal, frontal and transverse plane. A, positive values indicate flexion and negative values indicate extension. B, positive values indicate adduction and negative values indicate abduction. C, positive values indicate internal rotation and negative values indicate external rotation. The dotted line represents the sFAI group, the dashed line represents the aFAI group and the solid line represents the control group.

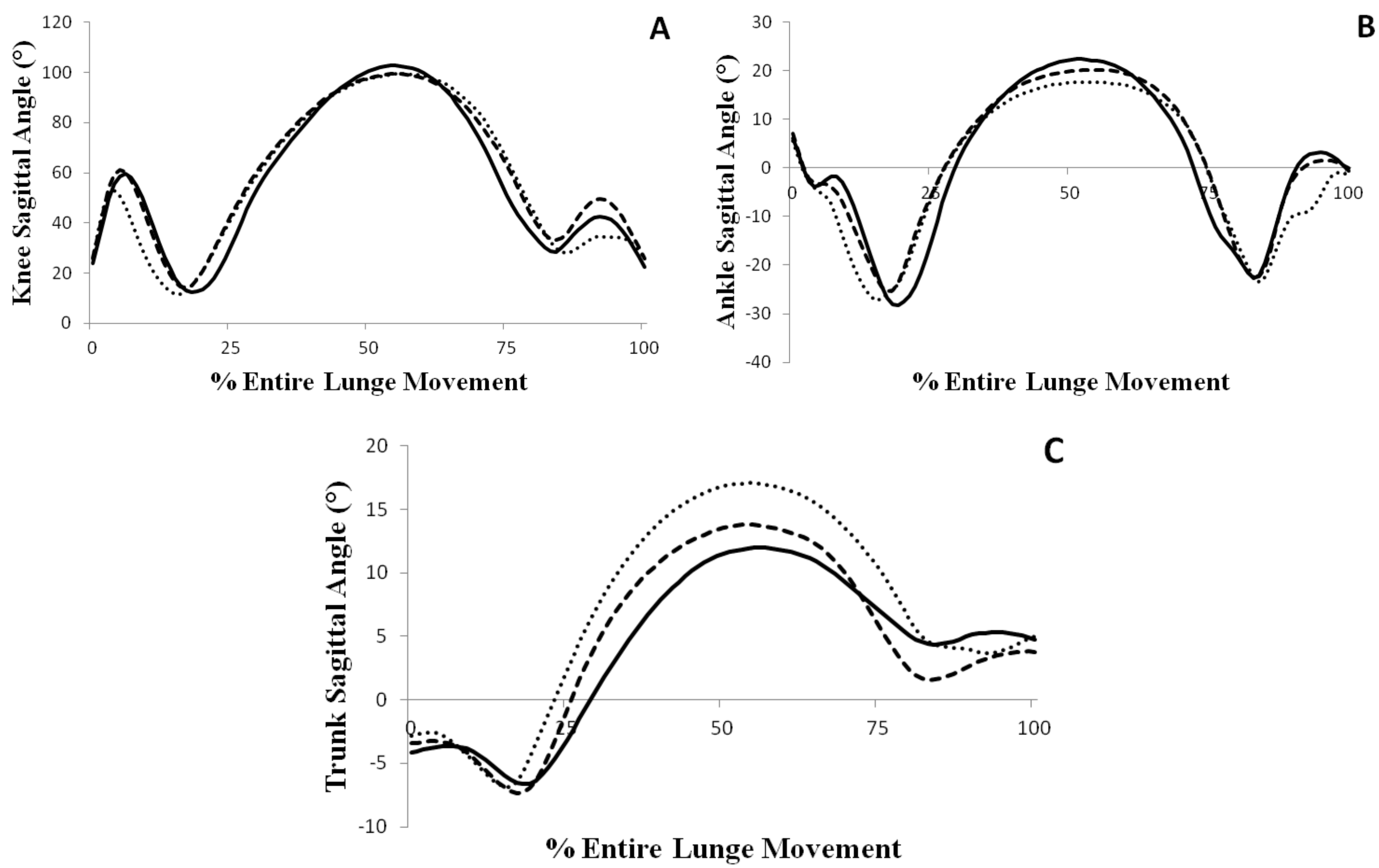

Figure 3.2: Kinematic ensemble averages of the knee, ankle and trunk in the sagittal plane. A, positive values indicate flexion and negative values indicate extension. B, positive values indicate dorsiflexion and negative values indicate plantarflexion. C, positive values indicate forward trunk flexion and negative values indicate extension. The dotted line represents the sFAI group, the dashed line represents the aFAI group and the solid line represents the control group.

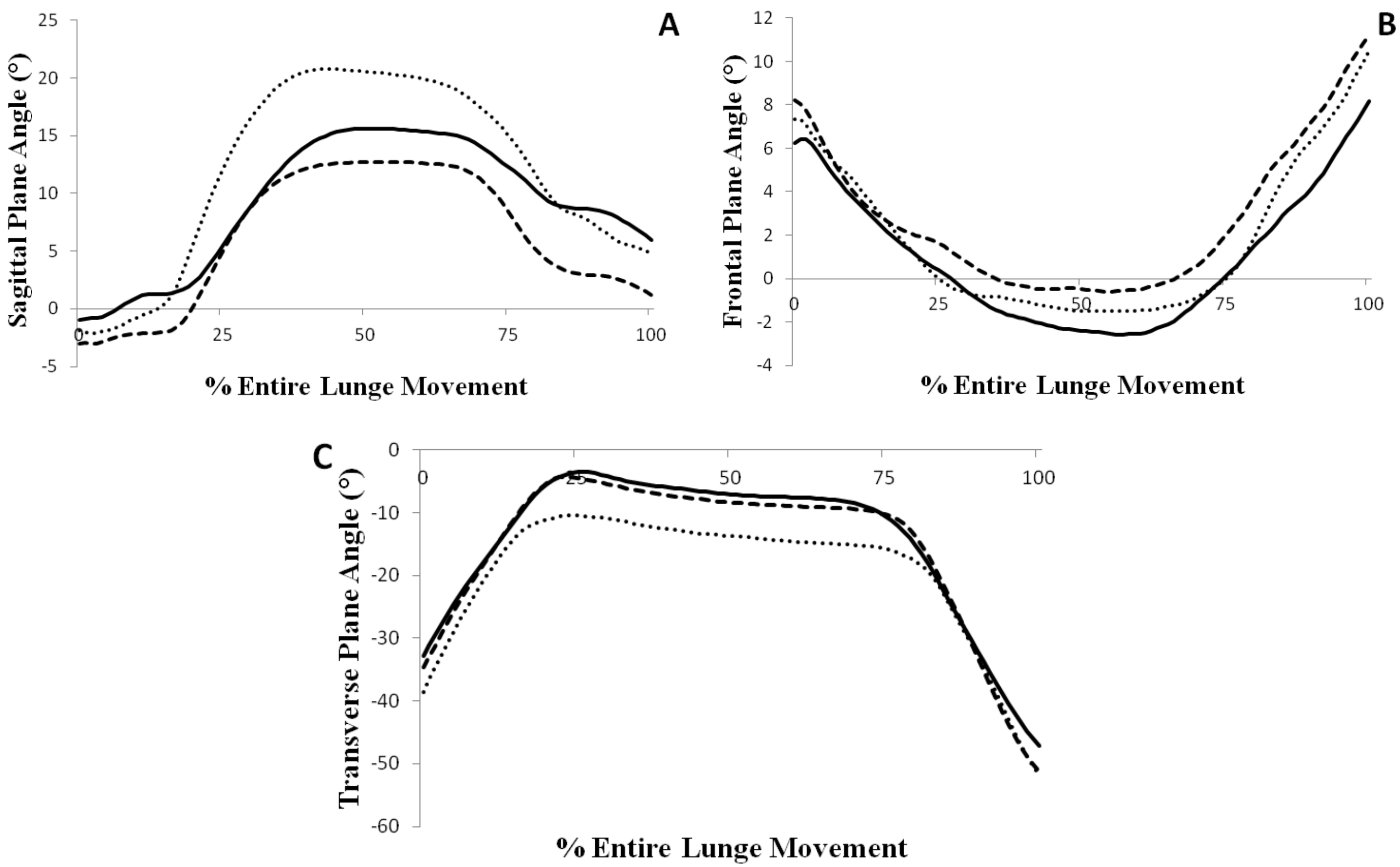

Figure 3.3: Kinematic ensemble averages of the pelvis in the sagittal, frontal and transverse planes. A, positive values indicate anterior tilt and negative values indicate posterior tilt. B, positive values indicate contralateral side flexion and negative values indicate ipsilateral side flexion. C, positive values indicate contralateral rotation of pelvis and negative values indicate ipsilateral rotation of pelvis. Contralateral and ipsilateral classifications are with respect to the lead limb performing the lunge. The dotted line represents the sFAI group, the dashed line represents the aFAI group and the solid line represents the control group.

3.6 Kinetic Outcomes

Kinetic variables were compared across the three groups and their values are reported in Tables 3.7, Table 3.8 and Table 3.9. Two outliers were identified, where one outlier was found for the hip frontal moment net impulse in one of the aFAI participants and one outlier was found for the knee sagittal moment net impulse in one of the control participants. Thus, after outlier removal, the hip frontal moment net impulse in Table 3.8 is from twelve aFAI participants instead of thirteen, and the knee sagittal moment net impulse in Table 3.8 is from ten control participants instead of eleven. For the peak external joint moments (Table 3.7), there were no statistically significant between-group differences for the hip sagittal plane ($p=0.244$), hip frontal plane ($p=0.450$), knee sagittal plane ($p=0.700$) and ankle sagittal plane ($p=0.090$). In terms of joint moment net impulses (Table 3.8), there were no statistically significant between-group differences found for the hip sagittal plane ($p=0.220$) or ankle sagittal plane ($p=0.234$). Prior to outlier removal, there were no statistically significant between-group differences found for hip frontal moment net impulse or knee sagittal moment net impulse. After outlier removal, the hip frontal moment net impulse remained statistically non-significant ($p=0.278$), but between-group differences for the knee sagittal moment net impulse became statistically significant ($p=0.007$). Specifically, the aFAI group had a statistically significantly larger knee sagittal moment net impulse [-10.55 s*(%BW*Ht) ± 3.31] than the control group [-7.15 s*(%BW*Ht) ± 1.95]. The difference in knee sagittal moment net impulse between the sFAI and control group approached statistical significance with a p value of 0.056. Group ensemble average curves for the joint moments are present in Figure 3.4 and Figure 3.5.

For the vertical ground reaction forces, there were no statistically significant between-group differences for the vertical ground reaction forces during lunge descent or ascent (Table

3.9) while performing the 45˚ cross-body lunge: largest lead limb vGRF during descent (p=0.376), largest lead limb vGRF during ascent (p=0.272), smallest trail limb vGRF during descent (p=0.428) or smallest trail limb vGRF during ascent (p=0.186). Group ensemble average curves for the lead and trail limb vGRF's are present in Figure 3.6.

Table 3.7: Peak external joint moments. Values are reported as mean (sd), unless otherwise reported.

Outcome	Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls	p values
Hip sagittal plane (%BW*Ht)	5.97 (2.51)	7.57 (2.10)	7.43 (2.30)	0.244
Hip frontal plane (%BW*Ht)	3.66 (1.15)	4.14 (0.76)	4.14 (1.01)	0.450
Knee sagittal plane (%BW*Ht)	-6.45 (1.28)	-6.56 (1.13)	-6.89 (1.28)	0.700
Ankle sagittal plane (%BW*Ht)	3.59 (1.01)	4.42 (0.83)	4.44 (1.01)	0.090

(+) values indicate hip flexion and adduction, knee extension, ankle dorsiflexion;
(-) values indicate hip extension and abduction, knee flexion, ankle plantarflexion;
Results are considered significant if $p<0.05$.

Table 3.8: Joint moment net impulses. Values are reported as mean (sd), unless otherwise reported.

Outcome	Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls	p values
Hip Sagittal Plane [s*(%BW*Ht)]	11.79 (7.20)	12.78 (3.64)	9.46 (4.88)	0.220
Hip Frontal Plane [s*(%BW*Ht)]	8.03 (3.72)	7.00 (1.60)	5.92 (2.20)	0.278
Knee Sagittal Plane† [s*(%BW*Ht)]	-12.97 (6.20)	-10.55 (3.31)	-7.15 (1.95)	0.007
Ankle Sagittal Plane [s*(%BW*Ht)]	7.07 (2.71)	6.65 (1.91)	5.52 (1.70)	0.234

† indicates statistically significant differences between the aFAI and control groups
(+) values indicate hip flexion and adduction, knee extension, ankle dorsiflexion;
(-) values indicate hip extension and abduction, knee flexion, ankle plantarflexion;
Results are considered significant if $p<0.05$.

Table 3.9: Vertical ground reaction forces. Values are reported as mean (sd), unless otherwise reported.

Outcome	Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls	p values
Lead limb largest value during descent (BW)	0.75 (0.12)	0.79 (0.06)	0.82 (0.12)	0.376
Lead limb largest value during ascent (BW)	0.79 (0.13)	0.85 (0.06)	0.85 (0.10)	0.272
Trail limb smallest value during descent (BW)	0.30 (0.10)	0.26 (0.04)	0.26 (0.07)	0.428
Trail limb smallest value during ascent (BW)	0.30 (0.08)	0.24 (0.05)	0.28 (0.09)	0.186

Results are considered significant if $p<0.05$.

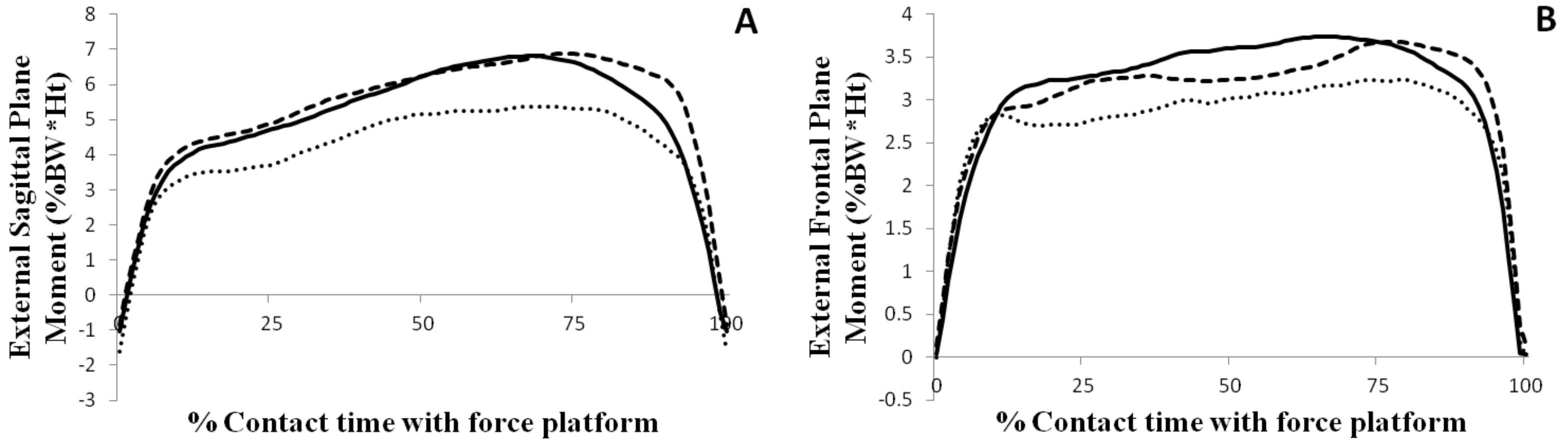

Figure 3.4: Kinetic ensemble averages of the hip in the sagittal and frontal planes. A, positive values indicate flexion and negative values indicate extension. B, positive values indicate adduction and negative values indicate abduction. The dotted line represents the sFAI group, the dashed line represents the aFAI group and the solid line represents the control group.

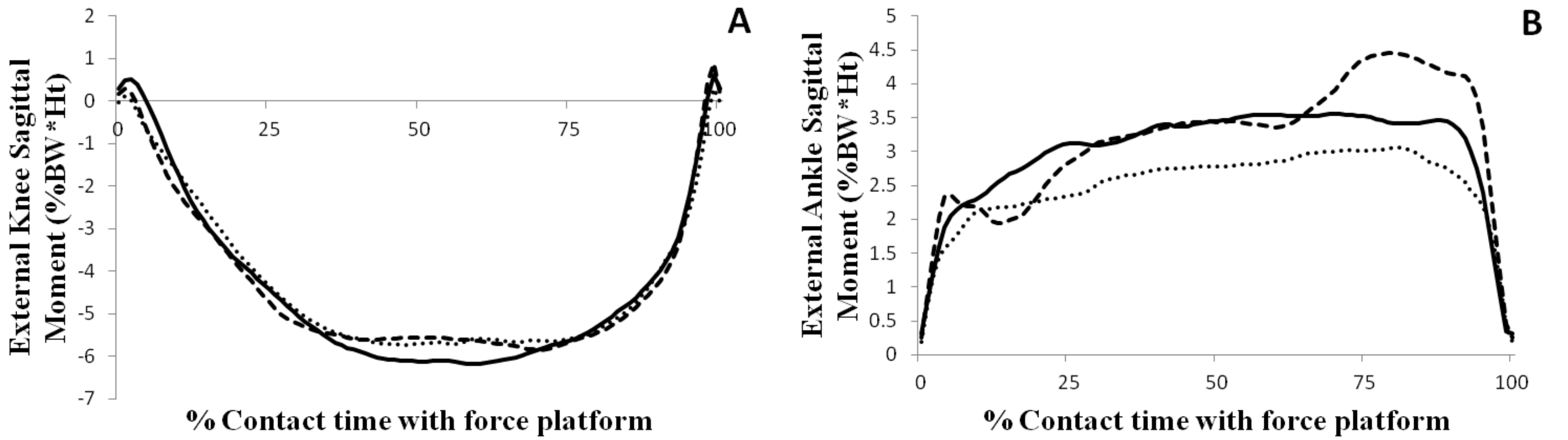

Figure 3.5: Kinetic ensemble averages of the knee and ankle in the sagittal plane. A, positive values are extension and negative values are flexion. B, positive values are dorsiflexion and negative values are plantarflexion. The dotted line represents the sFAI group, the dashed line represents the aFAI group and the solid line represents the control group.

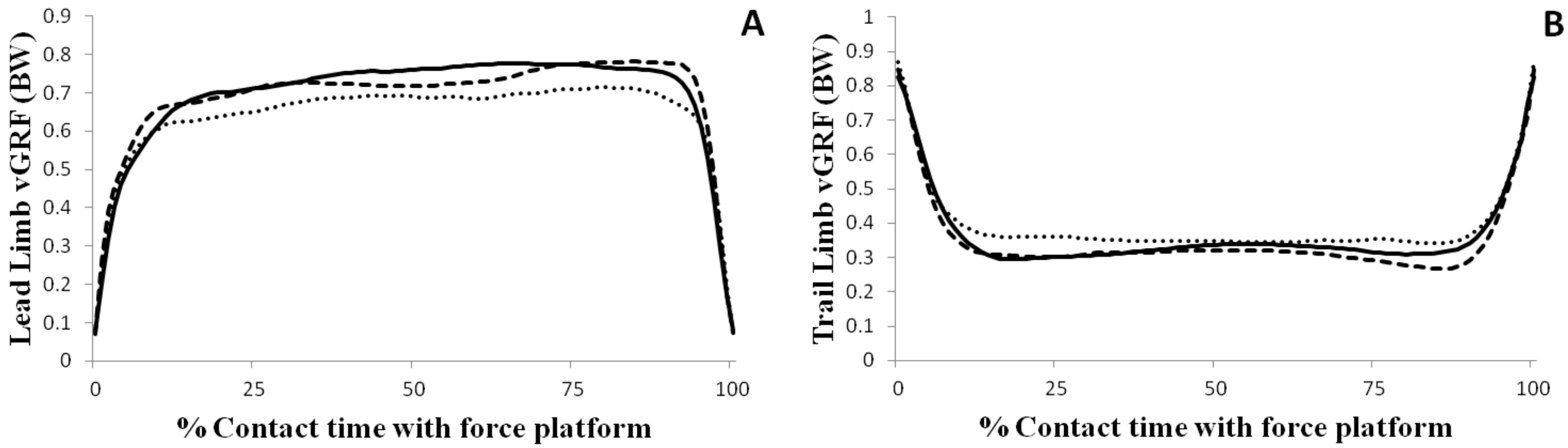

Figure 3.6: Ensemble averages of the lead limb and trail limb vertical ground reaction forces. The dotted line represents the sFAI group, the dashed line represents the aFAI group and the solid line represents the control group.

3.7 Participant reported outcomes after motion analysis

Pain values in the study (lead) limb hip, groin, knee and ankle, as measured on the NRS (0-10), and the number of participants that answered either 'yes' or 'no' to the question "does performing the 45° cross-body lunge reproduce the pain you typically experience?", are reported in Table 3.10.

Pain and discomfort in other body areas (both measured on the NRS) were also reported by participants while performing the 45° cross-body lunge. These areas included the thigh of the lead limb, lower back, foot of the trail limb, shoulder, knee of the lead and trail limb and shank of the lead and trail limb.

Table 3.10: Participant reported data after performing the 45° cross-body lunge. Values are reported as mean (sd), unless otherwise noted.

Outcome	Symptomatic FAI	Asymptomatic FAI	Asymptomatic controls
Pain (0-10)			
Hip	1.6 (1.6)	0.0 (0.0)	0.0 (0.0)
Groin	1.2 (1.3)	0.0 (0.0)	0.0 (0.0)
Knee	0.9 (2.7)	0.1 (0.3)	0.0 (0.0)
Ankle	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Does performing the 45° cross-body lunge reproduce the pain you typically experience? (Yes:No)	5:4	N/A	N/A

Chapter 4: Discussion

4.1 Interpretation of Findings

To the best of our knowledge, this is the first study to examine the biomechanics of a lunge movement in an FAI population. By specifically analyzing the 45˚ cross-body lunge, a movement that could likely provoke pain and impingement (due to the condition's patho-mechanism), statistically significant between-group differences could potentially be found that would be important for future FAI research and rehabilitation purposes. However, in general, our results showed a lack of statistically significant biomechanical differences among the sFAI, aFAI and control groups when performing the 45˚ cross-body lunge.

It was hypothesized that the sFAI group would exhibit decreased pelvis sagittal plane excursion and decreased frontal plane excursion during the entire lunge movement compared to the aFAI and control groups. It was expected that the sFAI group would limit the movement of the pelvis in the sagittal and frontal plane, as the lunge is a demanding movement that requires dynamic pelvis stability, due to the asymmetrical ground reaction force distribution in the two limbs. By limiting the pelvis motion in these two planes, the individuals with sFAI would theoretically limit the amount of movement leading to impingement (combination of end range hip flexion and hip adduction). In this study, there were, however, no statistically significant between-group differences in pelvis frontal plane excursion ($p=0.358$), possibly indicating similar levels of frontal plane pelvis control across all three groups. This finding is in contrast to a finding by Kennedy and colleagues (2009), who reported that individuals with sFAI exhibited a statistically significantly smaller pelvis frontal plane excursion than the control group during gait. The authors speculated that this difference could be due to a hip stabilization strategy adopted by individuals with sFAI to account for high amounts of frontal pelvis stability during walking or a restriction in pelvis mobility at the sacro-lumbar joint. Furthermore, a study by van Rensburg et al. (2017) found statistically significant differences at the pelvis in the frontal plane during a single-leg drop-landing task in individuals with chronic groin pain. Both the stance phase of gait and single-leg landing tasks are largely unipedal movements, and likely require a significant amount of control from the hip musculature responsible for pelvis frontal plane movement and control (e.g. gluteus medius). Thus, for these reasons, statistically significant differences were potentially found in the symptomatic participants compared to the controls in the previously mentioned studies. For our study, however, since no statistically significant findings were found for pelvis frontal plane excursion, this may lead us to believe that because the lunge is mostly a bilateral movement, the pelvis frontal plane requirement may not be enough to elicit statistically significant differences between FAI and non-FAI populations.

Prior to outlier removal, statistically significant between-group differences were found for pelvis sagittal plane excursion for the entire lunge ($p=0.045$), where a post-hoc analysis showed a statistically significant difference between the sFAI group (26.6˚ ± 10.2) and aFAI group (19.0˚ ± 4.8). As can be seen in Figure 3.3, this increased sagittal plane excursion in the sFAI group was the result of reaching a greater amount of peak anterior pelvis tilt. Numerically, this is further supported by no statistically significant differences in peak posterior pelvis tilt between groups (sFAI group (-3.8˚ ± 3.4); aFAI group (-4.9˚ ± 3.7); control group (-2.0˚ ± 1.9)), but larger amount of peak anterior pelvis tilt in the sFAI group (sFAI group (22.7˚ ± 10.6); aFAI group (14.1˚ ± 6.0); control group (18.0˚ ± 5.5)). Previous authors that have examined the deep squat have speculated that a smaller pelvis sagittal plane excursion during the deep squat can be counterproductive to the FAI pathology. Having the pelvis in a more anteriorly tilted position in the deeper parts of the squat puts the hip in a more flexed position, which has the potential to further provoke pain and induce earlier impingement in this population. At the deeper parts of the squat, the pelvis typically posteriorly tilts to allow for more hip flexion to occur, and the individuals with sFAI instead exhibit more anterior tilt, potentially demonstrating some deficits in sagittal plane control of the pelvis. Unlike the squat, because the lunge is in a split-leg position, where the pelvis position is counterbalanced from one hip being in large amounts of flexion and the other hip being in less flexion, the pelvis may not need to posteriorly tilt to allow for more hip flexion and can be in a more anteriorly tilted position.

A potential reason for differences in pelvis sagittal plane excursion is hip extensor muscle weakness (Catelli et al., 2018). In the paper by Catelli and colleagues (2018), the aFAI group had greater hip extension strength compared to the sFAI and control groups. With stronger hip extensors, the aFAI participants may have better control of the pelvis in the sagittal plane, which could result in the pelvis in a more posteriorly tilted position at the deeper parts of the squat and in less of a hip-flexed position. This could also help explain the larger pelvis sagittal plane excursion in our study, as the sFAI group exhibited a larger sagittal plane excursion than the aFAI group during the entire lunge. This difference between the sFAI and aFAI groups could potentially indicate that the sFAI participants in our study may have deficits in pelvis sagittal plane control, resulting in a larger excursion. However, after outlier removal, no statistically significant between-group differences were found for the pelvis sagittal plane excursion ($p=0.074$), so any potential explanations for pelvis sagittal plane excursion are merely speculative.

It was originally hypothesized that the sFAI group would exhibit smaller hip flexion and hip adduction angles at peak knee flexion as a compensatory movement because the combination of near-end range hip flexion and adduction can be an impingement-provoking position and may be uncomfortable and painful (Kolber et al., 2015). Furthermore, due to the nature of the task, where the participants were instructed to step as far as they could, it was expected that the sFAI participants would not step as far to avoid inducing large amounts of hip flexion. Despite the statistically non-significant findings, the sFAI group did exhibit about 5° more hip flexion than the other two groups. This could potentially be a result of the increased pelvis sagittal plane excursion (as previously discussed), however this is merely speculative. On a similar note, because this particular lunge required a large amount of hip adduction, it was expected that the sFAI group would exhibit a smaller hip adduction angle at peak knee flexion to avoid end-range hip adduction and impingement at the hip joint. However, no statistically significant between-group differences were seen. As discussed above, any potential compensations by the sFAI group to achieve similar hip adduction angles could be evident in pelvis motion. However, even the pelvis frontal plane excursion throughout the entire lunge was also not statistically significant among the groups, indicating that similar amounts of pelvis movement were exhibited in order to achieve similar hip adduction angles at peak knee flexion.

No statistically significant between-group differences were found for peak external hip flexion moment or trunk forward flexion at peak knee flexion. With greater trunk flexion, the centre of mass shifts more anteriorly, aiding in forward propulsion (Hammond et al., 2017) and also increasing the external hip flexion moment. As seen in the study by Hammond et al. (2017), the sFAI participants exhibited more trunk flexion than the healthy controls, possibly to increase the load on their hip extensors and decrease the load on their hip flexors. By decreasing the demand on their hip flexors, the soft tissue on the anterior aspect of the hip may get less aggravated from the bony impingement that might result from performing the 45° cross-body lunge. These reasons may still be potential explanations for our results as the sFAI group did exhibit larger amounts of trunk flexion throughout the movement and larger amounts of trunk flexion at peak knee flexion (albeit not statistically significant). However, with recent findings from Catelli et al. (2018) showing that individuals with sFAI exhibit both weaker hip flexor and extensor muscle strength, it could be possible that the sFAI participants in our study would instead exhibit a smaller peak external hip flexion moment to reduce the demand of the hip extensors. Moreover, it might also seem plausible that individuals with sFAI would instead exhibit smaller amounts of trunk flexion at peak knee flexion than the other two groups, moving their centre of mass more posteriorly and attempting to balance the demand of weak hip extensors and hip flexors (e.g. more erect trunk). Despite the prediction of increased trunk forward flexion at peak knee flexion, there were no statistically significant between-group differences in this variable in our study. Furthermore, because changes in forward trunk lean have shown to affect the external hip flexion moment (Farrokhi et al., 2008), the statistically non-significant findings in peak external hip flexion moment could also be attributed to the lack of statistically significant findings in forward trunk lean at peak knee flexion.

The non-statistically significant between-group differences in lunge depth did not match the majority of the squat literature as the sFAI group has shown to not squat as deep as the aFAI and control groups. While previous sFAI study participants likely exhibited a reduced squat depth to avoid experiencing pain, another potential reason for differences in squat depth is reduced pelvis sagittal plane excursion (Catelli et al., 2018; Lamontagne et al., 2009). With the pelvis in a more anteriorly tilted position near the deeper parts of the squat, this could potentially provoke impingement earlier in the squat downward movement, which might also prevent the sFAI participants from reaching a lower depth. Moreover, a reduced squat depth (and likely a reduced lunge depth as well), could also result from the different contributions from the hip, knee and ankle joints in these closed kinetic chain movements (Diamond et al., 2017; Lamontagne et al., 2009). In the study by Diamond and colleagues (2017), they found that the sFAI group squatted to a similar depth to the controls when a heel wedge was used and the influence of ankle dorsiflexion excursion was removed. For our study, however, the sFAI group lunged to a similar depth as the aFAI and control groups, but not because the influence of the ankle dorsiflexion excursion of the lead limb was removed. While the peak knee flexion angle for the sFAI group was about 4˚ smaller than the control group (albeit not statistically significant), a slightly larger hip flexion angle at peak knee flexion (about 5˚ more than the aFAI and control groups) and a slightly lower ankle dorsiflexion angle at peak knee flexion (about 5˚ more than the control group) all potentially contributed to offset any differences in lunge depth between the groups. Another potential contributor to a lack of statistically significant differences in lunge depth in our study could be the increased pelvis sagittal plane excursion in the sFAI group. While this variable was not statistically significant after an outlier was removed, the larger excursion likely allowed the sFAI group to produce more flexion at the hip joint, which in turn, contributed to achieving a similar depth as the other two groups.

The variable 'contact time with the force platform' trended towards statistical significance with a p value of 0.081. Specifically, the sFAI group exhibited a larger value for this variable (3.37 ± 1.75) compared to the aFAI group (2.49 ± 0.60) and control group (2.03 ± 0.67). Longer force platform contact time in the sFAI group supports previous work by Dwyer et al. (2016), where the authors found that the participants with symptomatic acetabular labral tears took longer to complete the forward lunge than the control participants. The authors commented that this finding was partly attributed to the statistically significantly smaller gluteus maximus EMG amplitudes during lunge ascent in the participants with symptomatic acetabular labral tears. With differences in gluteus maximus activity during this time frame, this likely resulted in a longer time to complete lunge ascent due to potential deficient concentric control.

Because EMG was not included in the current study, differences in hip muscle activity, particularly the hip extensors like gluteus maximus, cannot be determined. However, statistically significant differences have been found in gluteus maximus activity during the functional deep squat movement in a FAI population (Catelli et al., 2018) and thus may provide some important insight into another functional movement like the lunge. Moreover, there were no statistically significant between-group differences in lunge distance or peak knee flexion (i.e. maximal lunge depth). Lunge distance and peak knee flexion are important variables with regards to lunge duration, since as Dwyer et al. (2016) discussed, these variables can play a role in reversing forward momentum to return back to the lunge starting position. Since Dwyer and colleagues (2016) also found no statistically significant differences in these variables between symptomatic acetabular labral tear patients and controls, they discussed that a longer contact time during lunge ascent could instead be potentially explained by an impaired ability to recruit the gluteus maximus. Again, because no EMG was used in our study, we do not know whether statistically significant differences in hip muscle activity are present or if there are potential differences in recruitment ability. Finally, because increased duration can result in a larger impulse, differences in the ‘contact time with the force platform’ variable likely influenced the larger external knee sagittal moment net impulse values exhibited for both the sFAI and aFAI groups. However, since there were no statistically significant differences in ‘contact time with the force platform’, this is merely speculative.

Finally, there were no statistically significant between-group differences in the largest vGRF during lunge descent and ascent or the smallest vGRF during lunge descent and ascent.

These results are in contrast to the work by Dwyer et al. (2016) who reported that the symptomatic acetabular labral tear participants exhibited statistically significantly smaller vertical ground reaction forces during initial force platform contact than the control group. This was likely due to the larger sample size of participants in each group (21 participants with symptomatic acetabular labral tears and 17 control participants), as the participants with sFAI in our study still exhibited smaller vGRFs than the other two groups (albeit not statistically significant). Despite the statistical non-significance, a potential reason for this finding, as discussed by Dwyer and colleagues (2016), is that the sFAI participants are attempting to reduce the loading at the hip as a compensatory strategy from having experienced chronic hip and/or groin pain. In a similar light, because less loading was expected at the lead hip during the lunge, it was expected that the sFAI participants in our study would exhibit larger vGRF's in the trail limb during lunge descent and ascent than the aFAI and control groups. This was indeed the case, however the between-group differences were not statistically significant, potentially due to a relatively small sample size.

4.2 Study Limitations

This study is not without its limitations. One limitation is the relatively small sample size as having a small sample size may be a potential reason for the multiple statistically non-significant findings. Secondly, the study being cross-sectional in nature only allows for a snapshot of individuals with and without FAI when performing a 45° cross-body lunge. Because of this, only speculations can be made about any possible cause and effect relationship with regards to the findings of the study. However, because there was a lack of statistically significant results between the sFAI and aFAI groups, we are also not confident about the role of pain in distinguishing individuals with and without symptomatic FAI when performing a 45° cross-body lunge. Another limitation of this study is that EMG was not included in this study's protocol. While using EMG will likely have provided a better picture in terms of lunge kinetics, especially from a rehabilitation standpoint, a lack of statistically significant results were previously seen in a FAI population during another functional movement, stair-climbing (Hammond et al., 2017) and in a population similar to a FAI population (individuals with acetabular labral tears) performing a lunge (Dwyer et al., 2016). Since Catelli et al. (2018) recently demonstrated that statistically significant differences in biceps femoris, semitendinosus, rectus femoris and gluteus maximus activation were found when examining deep squat performance between sFAI, aFAI and control groups, using EMG to show hip and thigh muscle activity during a lunge may reveal important statistically significant differences between these same groups and should be the focus of future FAI research. Similarly, not including hip strength measurements in our protocol was a limitation in this study. A better understanding of between-group differences in pelvis sagittal plane excursion and external knee sagittal moment net impulse could have been achieved through assessing hip extensor and flexor strength.

Another limitation of this study is that imaging was not used to re-confirm the presence or absence of FAI as the participants of this study were recruited from a previous cohort and their FAI status was determined at initial enrollment. While it is possible that some of the asymptomatic controls exhibited imaging signs of FAI (e.g. alpha angle >55°, LCEA >40° and/or presence of crossover sign) in this study, previous research has shown that the alpha angle does not statistically significantly change over a 5 year period (Gala et al., 2016) and there were also no statistically significant changes in the LCEA and crossover sign, 20 years after periacetabular osteotomy (Steppacher et al., 2008). Furthermore, speed, distance, depth and participant trunk placement were not controlled for in this study to allow for participant self-selection and natural movement performance. However, because previous research has shown differences in lower limb biomechanics at varying trunk positions (Farrokhi et al., 2008), lunge lengths (Riemann et al., 2013), lunge speeds (Frost et al., 2015) and squat depths (Wretenberg et al., 1993), these parameters were self-selected to attempt to uncover differences between the three groups in this study. Finally, a between-sex analysis in 45° cross-body lunge performance was not conducted due to the small sample size in this study. Examining differences between males and females is important, as statistically significant between-sex differences were seen analyzing single leg step-down performance and gait in recent studies (Lewis et al., 2018a; Lewis et al., 2018b), and thus should be another focus of future research.

4.3 Future Directions

Although the results of our study suggest that there are minimal biomechanical differences in 45° cross-body lunge performance, further research is still required to aid in better explaining these results, and to potentially confirm or reject our findings.

4.3.1 Opportunities for Biomechanical Research

Future research should include EMG and hip strength measurements in lunge protocols. With information regarding hip and thigh musculature electrical activity and strength, particularly the muscles responsible for sagittal plane movement and control, one would be better able to tease out whether differences in muscle activity and/or strength are responsible for any biomechanical alterations (e.g. larger pelvis sagittal plane excursion). The trend in statistical significance in ‘contact time with the force platform’ (larger values in the sFAI and aFAI groups compared to the control group) may also be an indicator of underlying neuromuscular deficits (Dwyer et al., 2016). Thus, future research should include larger sample sizes, along with strength and EMG measurements, to determine if statistically significant differences in lunge duration exist between FAI and non-FAI populations and to determine which muscle(s) are potentially responsible for these statistically significant differences.

Future research on knee frontal and transverse plane kinetics during cutting or lunging can build upon our study's work in that larger amounts of sagittal plane loading are occurring about the knee in an FAI population. By looking at the other two planes, and knowing that there is a relationship between radiographic signs of FAI and ACL tears, it will allow researchers to better understand how the FAI condition can potentially negatively affect the knee joint. This will be even more important for clinician knowledge and rehabilitation as these athletes are experiencing these loads quite frequently. Comparing lunging or cutting maneuvers that are anticipated and unanticipated will also provide more information on tri-planar knee biomechanics, but more importantly, may uncover more statistically significant differences between FAI and non-FAI populations as unanticipated movements are more reflective of the movements performed during sports (Kim et al., 2014). Moreover, future research should examine more demanding high impact activities like running as they may uncover more important differences in the FAI population, particularly in frontal plane pelvis motion and in vGRFs. These movements may help researchers better understand any compensatory movements to achieve similar performance to controls, or reveal any muscular imbalances or altered loading that can significantly affect sport performance. Because our lunge protocol had multiple self-selected measures (speed, depth and distance) that did not elicit statistically significant differences, future lunge research should also consider constraining these parameters, similar to strategies seen in the FAI squat literature (Bagwell et al., 2016; Diamond et al., 2017).

In terms of future populations to be studied, because of the high prevalence of FAI in the athletic population, future research should focus on examining lunge performance in younger professional athletes with FAI. While few statistically significant differences were found in our study, we know from previous research that biomechanical differences exist when comparing different levels of sporting play. Thus, a biomechanical analysis on these athletes will greatly benefit clinicians and coaches, in that they would be better able to prescribe appropriate exercises for return-to-sport training or performance improvement.

Finally, future research should focus on developing longitudinal studies, where researchers would biomechanically assess individuals over time, from adolescence to FAI diagnosis. With this type of design, this would enable researchers to better determine any causative factors for FAI, considering the potential link between playing sports during adolescent bone growth and acquiring FAI later in life. Specifically, researchers may be able to determine whether differences in pelvis sagittal plane excursion when performing repetitive dynamic movements (like the lunge) during adolescent bone growth, for example, is a contributing factor to the development of FAI, or if the larger pelvis sagittal plane excursion is a compensatory strategy as a result of hip extensor muscle weakness.

4.3.2 Potential Impact for Clinical Practice

This was the first study to biomechanically examine the lunge in a FAI population. With this novel information, clinicians may be better able to more appropriately prescribe the lunge as an exercise (or any variation of it) for rehabilitation and return-to-sport training. This is important because (as mentioned above) the lunge is a sport-specific exercise and has been included in pre- and post-arthroscopy rehabilitation for individuals with FAI.

Most of our findings suggest that those with sFAI exhibit similar trunk, pelvis, hip, knee and ankle biomechanics and vGRFs during the 45° cross-body lunge compared to individuals with aFAI and healthy controls. This information may be clinically relevant as it can be potentially used as a reference point when initially assessing lunge performance in athletes with FAI. Thus, any alternate movement patterns exhibited by athletes may help inform clinicians when additional training or rehabilitation may be needed to better performance.

Having a larger pelvis sagittal plane excursion during the 45° cross-body lunge may impose some restrictions on sport performance in individuals with sFAI. This finding was potentially associated with weaker hip extensor muscles (as per the squat literature), however this is merely speculative as strength assessments were not conducted in our study. To aid in improving sport performance, particularly in sports with a high frequency of lunges, clinicians should potentially focus rehabilitation programs on strengthening the hip extensors like the gluteus maximus and the hamstring group. With strengthening these muscles, there may be improved control of the pelvis in the sagittal plane, which could translate into a smaller sagittal plane excursion and a more posteriorly tilted pelvis when reaching the lower lunge depths. With more posterior pelvis tilt, the individuals with sFAI may exhibit smaller degrees of hip flexion, which could help the athletes avoid pain and impingement when playing the sport. Movement retraining may also be important to improve control of the pelvis in the sagittal plane.

As for differences in knee sagittal moment net impulse, this is novel information that clinicians should potentially consider when designing rehabilitation and training programs. With a large amount of loading experienced by the knee in individuals with aFAI, there could be a higher chance of injury to the joint's soft tissues (Besier et al., 2001). Furthermore, the 45° cross-body lunge may involve frontal and transverse plane knee moments that can apply even more load on the ACL during a cross-over movement (Besier et al., 2001), which could significantly increase the chances of a tear. While not as important when performing the 45° cross-body lunge at a self-selected speed (like in this study), the consequences of performing this movement during the sporting activity at faster speeds while changing direction, may be detrimental for these athletes with aFAI. Considering further that there is a potential link between radiographic evidence of FAI and ACL tears (Boutris et al., 2018), the early involvement of training exercises with multidirectional movements may be critical to expose athletes with aFAI to constant frontal and transverse plane knee loading.

Finally, because the larger external knee sagittal moment net impulse in the aFAI and sFAI groups could have been attributed to the longer lunge duration ('contact time with the force platform'), movement re-training strategies (e.g. not lunging as deep) and knee musculature rehabilitative exercises should be potentially recommended by clinicians to avoid prolonged sagittal plane loading about the knee.

Chapter 5: Conclusion

The lunge is a commonly performed movement in sporting activities, rehabilitation and training. To our knowledge, this was the first study to examine lunge biomechanics in a FAI population. Overall, there was a lack of statistically significant between-group differences in 45˚ cross-body lunge performance. There was, however a statistically significant difference found in pelvis sagittal plane excursion before outlier removal and a statistically significant difference in knee sagittal moment net impulse after outlier removal. The sFAI group exhibited a larger pelvis sagittal plane excursion throughout the entire lunge compared to the aFAI group, and the aFAI group exhibited a larger knee sagittal moment net impulse compared to the control group.

These results have important rehabilitative and clinical implications, particularly for athletes in FAI-relevant sports like hockey, soccer, basketball, football and tennis. Knowing that individuals with sFAI exhibit a larger pelvis sagittal plane excursion throughout the 45˚ cross-body lunge and its potential effect on earlier pain and impingement provocation could better inform clinicians to prescribe more appropriate exercises. Because having the pelvis in a more posteriorly tilted position may help in avoiding pain and impingement, which can especially be important during sporting activity, strengthening hip extensor muscles like gluteus maximus and the hamstring group can be a critical component of return-to-sport rehabilitation. Furthermore, this study provided the FAI literature with novel information regarding differences in knee biomechanics in a movement requiring large amounts of hip flexion and adduction. Knowing that increased loads occur about the knee will provide more insight into the condition and its relationship to ACL tears, which could play an important role in training and distal injury prevention. The results from this study largely agree with the previous literature and suggest that there are minimal differences in movement biomechanics between sFAI, aFAI and healthy control populations. Future research should further examine differences in pelvis and knee biomechanics as they seem to play an important role in lunge performance in a FAI population.

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