Hip Joint Function in People with Femoroacetabular Impingement Syndrome

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HIP JOINT FUNCTION IN PEOPLE WITH FEMOROACETABULAR IMPINGEMENT SYNDROME

By
Philip Malloy, MS PT

A Dissertation submitted to the Faculty of the Graduate School, Marquette University, in Partial Fulfillment of the Requirement for the Degree of Doctor of Philosophy

Milwaukee, Wisconsin

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Femoroacetabular impingement syndrome (FAIS) is a clinical hip disorder that represents symptomatic contact between the proximal femur and rim of the acetabulum during normal hip range of motion. FAIS has been described as a precursor to hip joint osteoarthritis (OA), and results in physical impairments and functional limitations in young individuals and active adults. Despite tremendous growth in arthroscopic hip surgery for FAIS, little is known about how this disorder affects dynamic hip joint function. The purpose of this dissertation was to investigate hip joint function, during clinical and functional activities, both before and after arthroscopic hip surgery for FAIS.

The first aim compared hip joint function in people with FAIS to that of healthy matched controls. The results show that hip flexion muscle strength is reduced in people with FAIS, although, this loss of hip strength is not associated with gait kinetics or patient reported outcomes. These findings indicate that despite hip strength being impaired, people with FAIS can meet the functional demands of gait. However, during double and single leg squat tasks, significant alterations in hip joint biomechanics were found, and became greater as the control demand of the squat task were progressed. These findings indicate that FAIS alters hip biomechanics, however, tasks that require greater joint demand such as single leg squat are needed to bring about these alterations in joint function. The second aim examined hip joint function before and after hip arthroscopic surgery for FAIS. Arthroscopic hip surgery for FAIS did improve joint range of motion and muscle strength. Additionally, sagittal plane hip joint kinetics and hip joint kinematic control during gait changed after arthroscopic hip surgery, although, hip joint biomechanics remain different than healthy controls.

The aims of this dissertation demonstrate that clinical hip function is altered in people with FAIS and arthroscopic hip surgery improves this function. Tasks that involve end ranges of hip motion and single leg control are required to bring about alterations in hip joint biomechanics in people with FAIS. Gait biomechanics after arthroscopic hip surgery for FAIS change, however, may require an extended period to normalize after surgery.
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Philip Malloy, MS PT

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This dissertation is dedicated to my grandparents, (the late) Thomas and Margaret Malloy, who have embodied the meaning of love and faith for me throughout my life.
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I. INTRODUCTION

The concept of femoroacetabular impingement (FAI) was originally described by Ganz (2003) as a mechanism for the development of early onset osteoarthritis (OA) in hips without dysplasia (Ganz et al., 2003). FAI refers to the premature symptomatic contact at the hip joint during motion, which is secondary to a morphologic variation of the proximal femur and/or acetabulum (Ganz et al., 2003; Griffin et al., 2016). FAI is most commonly diagnosed in young individuals and active adults (Ganz et al., 2003). Radiographic evidence of FAI has been shown to be present in 85% of people between the ages of 18-50 years of age who are treated for hip pain (Ochoa, Dawson, Patzkowski, & Hsu, 2010). A recent prospective study found that 90% of people with FAI exhibit injury to the acetabular labrum and articular cartilage (Clohisy et al., 2013). It has also been postulated that approximately 50% of all cases of idiopathic hip OA may be linked to an underlying hip joint morphologic variation, such as FAI (Hack, Di Primio, Rakhra, & Beaule, 2010; HARRIS, 1986; Stulberg, Cordell, Harris, Ramsey, & MacEwen, 1975).

In the last year, the description and diagnosis of FAI has evolved to also include hip symptoms and clinical signs in addition to the radiographic diagnosis (Griffin et al., 2016). An international consensus expanded the concept of FAI to FAI syndrome (FAIS), which is defined as “a motion related clinical disorder of the hip with a triad of symptoms, clinical signs, and imaging findings” (Griffin et al., 2016). Commonly reported symptoms of FAIS include hip pain, catching, clicking, locking, and a feeling of instability (Griffin et al., 2016). The clinical signs of this hip disorder include reduced hip flexion and internal rotation range of motion, impairments in hip muscle strength, and the reproduction of symptoms during impingement testing (i.e. anterior impingement or FADIR test) (L. E. Diamond et al., 2015; Freke et al., 2016; Ganz et al., 2003; Griffin et al., 2016). Although this international consensus has expanded FAI beyond a mechanical concept to an actual clinical syndrome, little is known about the impact of FAIS on hip joint function.
Alarmingly, the rate of total hip replacement surgery for hip OA is projected to grow to half a million procedures annually by 2030 (Kurtz, Ong, Lau, Mowat, & Halpern, 2007). Therefore, a considerable effort has been made to develop surgical treatments for FAI with the goal of delaying or preventing the onset of hip OA (Bedi & Kelly, 2013). Arthroscopic hip surgery for FAI has grown exponentially since it was first described in 2003, with one study reporting a 600% increase in arthroscopic hip surgery between 2006 and 2010 (Bozic, Chan, Valone, Feeley, & Vail, 2013). A plethora of studies report good to excellent early and mid-term outcomes for the reduction of hip pain and improvement in patient reported function after arthroscopic hip surgery for FAI (N. C. Casartelli, Leunig, Maffiuletti, & Bizzini, 2015; Clohisy, St John, & Schutz, 2010; Gupta, Redmond, Stake, Dunne, & Domb, 2016; Levy et al., 2016; Matsuda, Carlisle, Arthurs, Wierks, & Philippon, 2011; Menge, Briggs, Dornan, McNamara, & Philippon, 2017; Nho, Magennis, Singh, & Kelly, 2011). Of great significance is that between 82% - 90% of individuals who undergo arthroscopic hip surgery for FAI report improved function and satisfaction after surgery (Levy et al., 2016; Sansone et al., 2017). Although these results are encouraging it remains unknown if arthroscopic hip surgery delays or prevents hip OA. In addition, no studies have reported improvements in the quantitative measures of hip joint function, such as hip range of motion or hip muscle strength, before and after surgical intervention (N. C. Casartelli, Maffiuletti, Item-Glatthorn, Impellizzeri, & Leunig, 2014; Tijssen, van Cingel, de Visser, & Nijhuis-van der Sanden, 2016).

Hip joint function can be measured with different objective physical performance measures that are used within the clinical and research settings. For example, in the clinical setting, hip joint function is commonly quantified through the measurement of hip joint range of motion and hip muscle strength (Krause, Schlagel, Stember, Zoetewey, & Hollman, 2007; Pua, Wrigley, Cowan, & Bennell, 2008). Additionally, clinicians often administer hip specific patient reported outcome scales to qualify the level of functional impairment or impact on quality of life in people with FAI. In the research setting, three-dimensional (3D) motion capture techniques
have been used to quantify joint function in people with a variety of hip joint disorders, including FAIS and hip OA (Bagwell, Snibbe, Gerhardt, & Powers, 2016; Foucher, Hurwitz, & Wimmer, 2007; Hunt, Gunether, & Gilbart, 2013; Hurwitz, Hulet, Andriacchi, Rosenberg, & Galante, 1997; Kennedy, Lamontagne, & Beaulé, 2009; Kumar et al., 2014; Lamontagne, Kennedy, & Beaulé, 2009; Lamontagne, Brisson, Kennedy, & Beaule, 2011; J. Rylander, Shu, Favre, Safran, & Andriacchi, 2013; J. H. Rylander, Shu, Andriacchi, & Safran, 2011; Samaan et al., 2015; Samaan et al., 2016).

For the following studies, hip joint function is defined as any quantitative clinical or biomechanical measure that indicates physical performance of the hip joint during both physical evaluation and functional tasks, such was walking and squatting.

Two recent systematic reviews found that reduced hip range of motion and muscle strength are the most common impairments in function in people with FAIS (L. E. Diamond et al., 2015; Freke et al., 2016). Additionally, these measures have been found to be important indicators of how the disease impacts people with FAIS (Reiman, Thorborg, Covington, Cook, & Holmich, 2017). The evidence of biomechanical hip joint function in people with FAIS is limited and inconclusive (Bagwell et al., 2016; Hunt et al., 2013; Lamontagne et al., 2009; J. Rylander et al., 2013; J. H. Rylander et al., 2011; Samaan et al., 2016). Alterations in gait kinematics and kinetics have been reported in people with FAIS when compared to healthy controls, however, other studies have reported no difference between these groups (L. E. Diamond et al., 2016; Hunt et al., 2013; Kennedy et al., 2009; Kumar et al., 2014; Samaan et al., 2016). Interestingly, studies that evaluate tasks involving terminal ranges of hip motion, such as a double leg squat, demonstrate more consistent differences in biomechanical hip function between people with FAIS and healthy controls (Bagwell et al., 2016; L. Diamond et al., 2017; Kumar et al., 2014; Lamontagne et al., 2009). The impact of surgical interventions on biomechanical joint hip function is generally limited and demonstrates mixed results (Brisson, Lamontagne, Kennedy, & Beaulé, 2013; Lamontagne et al., 2011; J. Rylander et al., 2013; J. H. Rylander et al., 2011). Perhaps the primary reason for this inconsistency is that these studies have evaluated different
types of surgical procedures for FAIS (i.e. arthroscopic vs. open) (Brisson et al., 2013; Lamontagne et al., 2011; J. Rylander et al., 2013; J. H. Rylander et al., 2011). Additionally, most biomechanical analysis of hip joint function in people with FAIS has been limited to discrete variable analysis where a single time point is selected \textit{a priori} to represent the most salient feature of the biomechanical time series data. A limitation to this type of analysis is that a large amount of the biomechanical time series data are disregarded during the analysis. Therefore, perhaps more robust analytic methods should be used to quantify potential biomechanical alterations in hip joint function in people with FAIS.

The use of multivariate statistics and non-linear analysis techniques to analyze biomechanical waveform data have become increasingly popular (Astephen, Deluzio, Caldwell, & Dunbar, 2008; K. J. Deluzio, Wyss, Zee, Costigan, & Serbie, 1997; K. Deluzio & Astephen, 2007; Kipp & Palmieri-Smith, 2013; Kipp, McLean, & Palmieri-Smith, 2011; Muniz & Nadal, 2009; O'Connor & Bottum, 2009; Samaan et al., 2015; Wrigley, Albert, Deluzio, & Stevenson, 2005). These techniques avoid the need to select \textit{a priori} biomechanical variables to represent the important features of a movement pattern during a functional task (O'Connor & Bottum, 2009). Furthermore, these techniques have also been shown to be more sensitive for detecting between group differences in biomechanical variables (O'Connor & Bottum, 2009; Wrigley et al., 2005). Recently, alterations in lower limb segment and hip muscle coordination patterns have been found in people with hip chondral injury and FAIS (L. E. Diamond et al., 2017; Samaan et al., 2015). Therefore, the application of these analytic techniques for the measurement of movement control during function in people with FAIS before and after arthroscopic hip surgery is novel and could provide further evidence for impairments in neuromuscular control in persons with FAIS. This evidence can also help guide functional neuromuscular training exercises for FAIS by demonstrating specific targets, such as a plane of motion or specific hip muscle group. In addition, these techniques evaluate the temporal structure of the biomechanical waveform, therefore could be useful to help identify a period of interest during a functional task.
To improve the understanding of the impact of FAIS on hip joint function, the two specific aims of this dissertation were to: 1) compare clinical and biomechanical measures of hip joint function in people with FAIS and healthy controls, and 2) to compare hip joint function before and after arthroscopic hip surgery for FAIS. The central hypotheses were that: 1) people with FAIS will demonstrate impairments in clinical measures of hip function characterized by reduced hip joint range of motion and hip muscle strength when compared to healthy controls, 2) people with FAIS will demonstrate alterations in hip biomechanics characterized by smaller peak kinematic and kinetic variables and alterations in movement patterns during functional tasks such as walking and squatting, 3) individuals will demonstrate improved clinical measures of hip function after arthroscopic hip surgery characterized by greater joint range of motion and hip muscle strength after surgery, 4) individuals will demonstrate improved hip joint biomechanics during walking such that they resemble that of healthy controls after arthroscopic hip surgery for FAIS.

This dissertation includes 4 manuscripts, each of which will inform an aspect of the specific aims. The first two manuscripts inform Aim #1, whereas the final two manuscripts inform Aim #2. The focus of the first manuscript is to analyze clinical measures of hip function in people with FAIS when compared to healthy controls. This manuscript looks to determine if associations exists between clinical and biomechanical measures of function during gait and patient reported outcomes. The second manuscript examines whether changing the joint control demands of a squat task influences biomechanical alterations in people with FAIS compared to healthy controls. The third manuscript explores the alterations in clinical and biomechanical measures of hip function within individuals who undergo arthroscopic hip surgery for FAIS and compares postoperative individuals to healthy controls. The final manuscript uses multivariate statistical analysis to examine hip joint kinematic control before and after arthroscopic hip surgery for FAIS. Together these manuscripts provide a comprehensive examination of alterations in hip function in people with FAIS that will serve two primary goals: 1) to add to the
emerging quantitative evidence on hip joint function in people with FAIS before and after arthroscopic hip surgery; 2) to help identify specific areas of hip function for future research aimed at better understanding the dynamic impact of this disorder in the context of symptom development and disease progression.
II. HIP MUSCLE STRENGTH IS NOT RELATED TO BIOMECHANICAL HIP JOINT FUNCTION DURING GAIT OR PATIENT REPORTED OUTCOMES IN PEOPLE WITH FEMOROACETABULAR IMPINGEMENT SYNDROME

Introduction

Femoroacetabular impingement (FAI) results from the symptomatic premature contact between the femur and acetabulum, and is the consequence of a structural anomaly of the hip joint (Ganz et al., 2003). Cam type FAI arises from the proximal femur and is defined as a lack of offset between the femoral head and neck junction (Bedi & Kelly, 2013; Ganz et al., 2003). Pincer type FAI occurs on the acetabulum and can result secondary to coxa profunda, os acetabuli, or focal acetabular retroversion (Bedi & Kelly, 2013). When these types of FAI occur in combination this is referred to as mixed type FAI (Bedi & Kelly, 2013). What is of concern is that these morphology’s are directly linked to injuries to the acetabular labrum and articular cartilage, and are implicated in the development of secondary hip osteoarthritis (OA) (Beck, Kalhor, Leunig, & Ganz, 2005; Bedi & Kelly, 2013; Ganz et al., 2003). Traditionally, the diagnosis of FAI was based solely on imaging findings. However, a recent international consensus has expanded the definition of FAI to FAI syndrome (FAIS), which now extends the criteria for diagnosis to also encompass patient symptoms and clinical signs (Griffin et al., 2016). Some common symptoms and clinical signs of FAIS are anterior hip pain, range of motion limitations, reduced hip muscle strength, and the reproduction of symptoms with combined flexion, adduction, and internal rotation (i.e. impingement test) (N. Casartelli et al., 2011; Clohisy et al., 2009; L. E. Diamond et al., 2016; Freke et al., 2016; Harris-Hayes et al., 2014). In addition, people with FAIS report functional limitation during activities such prolonged walking, sitting, squatting, and pivoting (Clohisy et al., 2009; Philippon, Maxwell, Johnston, Schenker, & Briggs, 2007). Although the expanded definition of FAIS provides clinicians and researchers with a more holistic approach for its diagnosis and treatment, to our knowledge, no study has investigated the
associations among the clinical signs of FAIS and quantitative and qualitative measures of function.

Reduced hip flexion and abduction muscle strength is a common clinical sign in people with FAIS and chronic hip pain (N. Casartelli et al., 2011; Freke et al., 2016; Harris-Hayes et al., 2014). Most notably, a recent systematic review found that reduced hip muscle strength and altered balance are the most common physical impairments in people with FAIS (Freke et al., 2016). Casartelli and colleagues found that people with FAIS displayed lower hip flexion, adduction, external rotation, and abduction strength compared to healthy controls (N. Casartelli et al., 2011). Similarly, people with symptomatic acetabular labral tears, a common consequence of FAIS, also demonstrate less hip flexor strength when compared to healthy controls (Mendis, Wilson, Hayes, Watts, & Hides, 2014). In addition, people with chronic hip joint pain also exhibit less hip abduction, external and internal rotation muscle strength when compared to healthy controls (Harris-Hayes et al., 2014). These combined results are significant because it has been recently reported that hip strength is an important measure of disease impact in people with FAIS (Reiman et al., 2017). Despite this evidence of reduced hip muscle strength in people with FAIS, it remains unknown as to whether strength impairments translate to alterations in biomechanical hip joint function or limitation in patient reported function and reduced quality of life.

Three-dimensional (3D) motion analysis is a quantitative method commonly used to study biomechanical hip joint function in people with hip pathology (Foucher et al., 2007; Hunt et al., 2013; Kennedy et al., 2009; Lamontagne et al., 2011; J. H. Rylander et al., 2011). Studies have found that biomechanical measures of hip function during gait differ between people with FAIS and healthy controls (Hunt et al., 2013; Kennedy et al., 2009). In particular, researchers have noted differences in hip kinetics, characterized by smaller peak hip flexion and external rotation moments during gait compared to healthy controls (Hunt et al., 2013). Similarly, alterations in hip and pelvic frontal and sagittal plane kinematics have also been reported in people with FAIS (Hunt et al., 2013; Kennedy et al., 2009; J. H. Rylander et al., 2011). The
differences in biomechanical hip joint function during gait are most consistent in the sagittal and frontal planes, which is not surprising based on the importance of the hip flexor and abductor muscles in maintaining hip and pelvic control during normal gait (van der Krogt, Marjolein M, Delp, & Schwartz, 2012). However, it remains unknown as to whether alterations in hip joint kinetics are related to strength impairment of the hip flexor or abductor muscles. Therefore, the investigation of the association between hip muscle strength and hip joint kinetics during gait is warranted as this could help provide rationale for hip muscle strengthening in people with FAIS and provide insight into the patho-mechanics of this hip disorder.

Patient reported outcomes (PROs) are developed through qualitative methods to assess disease burden, symptoms, and quality of life and are commonly implemented for people with musculoskeletal pathology (Cheng & Clark, 2017). The original PROs for people with hip pathology were designed to measure function in persons with degenerative hip osteoarthritis (Hoeksma, Van Den Ende, Ronday, Heering, & Breedveld, 2003). In recent years, PROs have been developed specifically for people with hip pathology such as FAIS (Christensen, Althausen, Mittleman, Lee, & McCarthy, 2003; Martin et al., 2010; Mohtadi et al., 2012). The Hip Outcome Score Activity of Daily Living Scale (HOS-ADL), Nonarthritic Hip Score (NAHS), and International Hip Outcome Tool 33 (iHot 33) are three PROs that are valid and reliable for the measure of overall function and quality of life in people with FAIS (Christensen et al., 2003; Harris-Hayes et al., 2013; Martin, Kelly, & Philippon, 2006; Martin & Philippon, 2008; Mohtadi et al., 2012). The information gained from these PROs is often used to guide treatment and track meaningful progress during rehabilitation in people with FAIS. Interestingly, measures of leg extensor power showed a strong association with self-reported pain and physical function in people with hip osteoarthritis (Juhakoski, Tenhonen, Anttonen, Kauppinen, & Arokoski, 2008). However, it remains unknown if similar associations exist between hip muscle strength and PROs in people with FAIS.
Multiple studies have demonstrated associations between muscle weakness and common musculoskeletal syndromes although no evidence exists for FAIS (Allison et al., 2016; Fredericson et al., 2000; Khayambashi, Mohammadkhani, Ghaznavi, Lyle, & Powers, 2012). Therefore, an improved understanding of the associations between hip muscle strength and quantitative and qualitative measures of function could help improve physical therapy treatments for people with FAIS and provide insight into the patho-mechanics of this clinical hip disorder. The purpose of this study was to investigate the role of hip muscle strength in relation to biomechanical measures of hip function during gait and PROs in people with FAIS. We hypothesized that people with FAIS would demonstrate less hip flexion and abduction muscle strength than healthy controls, and that the extent of loss of muscle strength would correlate with a reduction in peak hip kinetics during gait and with the lower HOS-ADL, NAHS, and iHOT 33 measures of function and quality of life.

Methods

Participants

Twenty people diagnosed with FAIS and 20 healthy controls matched for gender, body mass, and height participated in this study. All people with FAIS were diagnosed by a single orthopedic surgeon who specializes in the treatment of hip disorders. The criteria for diagnosis of FAIS included all of the following: 1) hip pain ≥ 3 months; 2) a positive anterior impingement (FADIR) test; 3) radiographic evidence of cam or pincer type morphology defined by any of the following: alpha angle >55° (cam type); center edge angle >40° (pincer type); or confirmed crossover sign (pincer type); 4) Tonnis grade ≤ 1 on standard radiograph; 5) magnetic resonance imaging with no evidence of diffuse articular cartilage degeneration; 6) positive response to an intra-articular anesthetic injection was defined as patient reported temporary pain relief during
impingement testing and other patient specific provocative maneuvers that occurred immediately after the injection.

All control participants were recruited from a general local university population. A physical screening examination was performed on all control participants to rule out potential cam or pincer type morphology. The screening examination consisted of passive range of motion (PROM) measurement and a hip joint physical examination. The physical examination consisted of the anterior impingement test (FADIR test), FABER test, Log roll test, and the dial test (Byrd, 2007; Ganz et al., 2003; Martin, Irrgang, & Sekiya, 2008; Martin et al., 2010; Philippon et al., 2007). Participants were excluded if any examination technique elicited anterior groin or lateral hip pain. Control participants were also excluded if they reported any of the following: (1) pain in any other lower extremity joint, (2) significant low back or lower extremity injury within the last 6 months, (3) history of back or lower extremity surgery on the test leg, (4) history of hip fracture or dislocation, (5) previous diagnosis of any developmental hip conditions, and (6) any systemic disorders that limit the performance of activities of daily living, (7) hip joint PROM < 85° of hip flexion PROM and < 10° of internal rotation at 90° of flexion secondary these cutoffs being associated with underlying FAI (Bedi & Kelly, 2013; Nepple et al., 2013). The study was approved by the local university’s office of research compliance. All participants provided a written informed consent before participation in the study.

Hip Muscle Strength Testing

Both hip flexion and abduction muscle strength are defined as a maximal, isometric internal torque produced by maximal volitional effort. With the assumption of static and rotary equilibrium during the testing, it is assumed that the internal torque is equal to the measured external torque. External torque is calculated as the product of the measured isometric external force (N) in the direction of hip extension or adduction and the femoral length (m). Isometric external force (N) was measured using a hand-held dynamometer (Lafayette Instruments;
Lafayette, Indiana) by a single examiner (PM). Femoral length (m) was measured as the distance between the greater trochanter and the lateral femoral epicondyle, Maximal external torque (N-m) was calculated as the product of the measured external force (N) and femoral length (m). All hip muscle strength measures were normalized to the participants body mass (N·m·kg). All hip muscle testing directed the participants to gradually increase force, and to produce a maximal force output for 3 seconds. Three maximal isometric contractions were collected on each leg and the average of the three trials for each leg was calculated and used for analysis. A 20 second rest period was given between each contraction to prevent fatigue. To measure the reliability of hip muscle strength a test-retest pilot study was conducted on 5 individuals with the average time between testing sessions being 10 ± 5.2 days. Cronbach’s alpha statistic was used to assess test-retest reliability. The Cronbach’s alpha values were .974, and .960 for hip flexion and hip abduction muscle strength testing, respectively. The results indicate excellent test-retest reliability for the hip muscle strength tests in the current study.

Hip flexion muscle strength was measured in the seated position with the participants hip at 80 degrees of flexion, which was confirmed by goniometric measurement. The participants placed each hand flat on the table beside their hip’s and were instructed to not hold the side of the table during testing. The pad of the hand-held dynamometer was placed on the anterior aspect of the distal thigh with the bottom edge of the pad in line with the lateral epicondyle of the femur (Figure 1). Participants were instructed to attempt to lift the thigh towards the ceiling pressing upward into the dynamometer.
Figure 1. Isometric hip flexion strength testing

Hip abduction muscle strength was measured with the participant in the side-lying position. The test hip (i.e. top leg) was placed in neutral rotation in all planes, which was confirmed by goniometric measurement. The bottom leg was placed in a position of mid-range hip and knee flexion to provide stability during testing. The hand-held dynamometer was placed in a custom foam pad to prevent slipping and discomfort on the lateral thigh during testing. The pad was aligned so that the inferior edge was in line with the knee joint line and the center of the dynamometer pad was in line with the lateral epicondyle of the femur. The dynamometer was placed so that it faced upward and was secured in place with a canvas strap that was secured around the treatment table (Figure 2). The examiner placed a stabilizing hand on the iliac crest of the test leg to prevent pelvic movement during the test. The participant was instructed to raise the test leg toward the ceiling pressing into the foam pad.
Patient Reported Outcomes of Function

All FAIS participants completed self-reported measures of hip function and quality of life. The Hip Outcome Score Activity of Daily Living Subscale (HOS-ADL) is a reliable and valid measure of self-reported physical function for people with intra-articular hip injury undergoing hip arthroscopy (Martin et al., 2006; Martin & Philippon, 2008). The HOS-ADL demonstrated both convergent and divergent validity when compared to the SF-36 physical function subscale. Pearson correlation coefficients were greatest between the HOS-ADL and SF-36 physical function ($r = .76$) and physical component score summary ($r = .74$). Expectedly, the correlations were lowest between the HOS-ADL and SF-36 mental health subscale ($r = .27$) and mental component summary score ($r = .18$). Additionally, internal consistency using the Standard Error of Measure (SEM) was high for the HOS-ADL (.96), which indicates that the measure has high precision when measured at a single time point (Martin et al., 2006). The minimal detectable change for the HOS-ADL was shown to be ± 3 points and the minimally clinical important difference was 9 points (Martin & Philippon, 2008). The HOS-ADL is a 17-item scale with each item being scored from 4-0, in which a 4 represents “no difficulty” and 0 represents “unable to do”. The total item score is represented by the sum of all the items, with a maximum score of 68.
The item score is then divided by the highest potential score of 68 and multiplied by 100 to determine the percent of functional limitation (Martin et al., 2006; Martin & Philippon, 2008).

The Nonarthritic hip score (NAHS) is a reliable and valid measures of functional performance of the hip that was designed to be used for younger patients with hip pain who engage in activities of higher demand. The NAHS is aimed at 20-40-year-old patients with hip pain and addresses four domains: pain, mechanical symptoms, physical function, and activity level. The scoring includes 20 multiple choice questions with 5 responses, each of which corresponds to a value. The values are summed and multiplied by 1.25 to obtain the final score. NAHS demonstrated excellent test-retest reliability ($r = .96$) and high convergent and construct validity ($r = .82$) when the NAHS was compared to the Harris Hip Score using Pearson correlation coefficients (Christensen et al., 2003). No measures of minimal detectable change or minimally important difference have been reported for the NAHS.

The International Hip Outcome Tool 33 (iHot 33) is a reliable and valid measure of measure quality of life in young active patients with symptomatic hip disease. The iHot 33 is a 33-item scale that measures quality of life across the domains of: recreational and occupational activities, social, emotional, and lifestyle concerns. Each item is measured on a 100-mm visual analog scale (VAS). Each end of the VAS represents opposite parameters, such as “extreme difficulty” vs. “not difficult at all”. The average VAS scores for each item are averaged to calculate the iHot 33 score with the maximum possible score being 100, which represents no impairment in quality of life (Mohtadi et al., 2012). Test re-test reliability for the iHot 33 was very good with the Chronbach’s $\alpha = 0.99$. The construct validity was assessed through correlation with the Nonarthritic Hip Score, and demonstrated a strong correlation ($r = 0.81$) with this outcome measure. The iHot 33 was also shown to be responsive and demonstrates a minimal clinically important difference of 6 points (Mohtadi et al., 2012).
Gait Data Acquisition

Three-dimensional position data of reflective markers were collected at 100Hz with a 14-camera motion analysis system (Vicon Motion Systems Ltd. London, UK). Three-dimensional ground reaction force data were collected simultaneously at 1000Hz with two floor embedded force plates (AMTI Watertown, MA, USA) positioned in series in a 10-m walkway. Forty-five retroreflective markers were attached to anatomic landmarks of each participant (Figure 3). A two second static standing trial with all markers was collected to define segment parameters and to estimate joint center locations. Then all single markers except those on the pelvis, trunk and lower extremity marker clusters were removed for movement testing which left 29 markers for gait testing. All participants were asked to walk at their self-selected speed along a 10-m walkway. Five successful trials were collected for the test leg of all participants. The definition of a successful trial was when the participants foot made complete contact with one of the force plates. Initial contact during a gait trial was defined as when the vertical ground reaction force (vGRF) exceeded 15 N and toe off was defined as when this vertical force became less than 15 N after initial contact. The next heel strike was defined using a heel marker coordinate based algorithm, which is defined as when the distal heel markers vertical position was at its global minimum following the previous toe off identified from the vGRF (Zeni, Richards, & Higginson, 2008).
Data Processing and Analysis

Visual 3D (C-Motion, Inc, Rockville, MD) was used to process raw position and ground reaction force data. A 4\textsuperscript{th} order low pass Butterworth filter with a cutoff frequency of 6Hz was used to filter raw position and ground reaction force data. An 8-link segment kinematic model was built in Visual 3D using the CODA pelvis (Charnwood Dynamics Ltd. Leicestershire, UK). Joint coordinate systems were created using an unweighted least squares approach to determine segment position and orientation ( Spoor & Veldpaus, 1980). A Cardan rotation sequence of X-Y'-Z" was applied to the joint coordinate systems such that this sequence represented the medial-lateral, anterior-posterior, and superior-inferior directions. All joint angles during movement trials were normalized to the static standing trial. An inverse dynamics approach was used to calculate all net internal joint moments during gait. Peak hip flexion and abduction moments were extracted from the non-time normalized kinetic waveforms and were normalized to body mass (N·m·kg\textsuperscript{-1}). Ensemble averages from 5 full strides of gait were calculated for peak hip flexion and abduction moments for each participant and used for analysis. Positive values represent flexion and adduction and negative values represent extension and abduction. Following extraction of...
peak joint moments, all kinetic time series data were normalized to 100 data points to represent a full gait cycle.

The center of mass (CoM) of the model was calculated based on a weighted average of the masses of all the kinetic segments included in the model (i.e. segments used in inverse dynamic calculations). The CoM was a virtual point located within the center of the pelvis segment based on the segments contained in the model. Gait speed was defined as the average center of mass (CoM) velocity (m·s\(^{-1}\)) during a full stride of gait. CoM velocity was calculated as the first derivative of CoM position during a full non-time normalized stride of gait. A 5-trial ensemble average was calculated for each participant to represent each participant’s gait speed.

**Statistical Analysis**

All data were examined prior to analysis to determine if parametric statistical assumptions were met. In cases where date violated parametric statistical testing assumptions, the appropriate non-parametric analog test was used for analysis. Independent samples t-tests and Mann-Whitney U tests were used to determine between group differences for all variables of interest. In addition, effect sizes (ES: Cohen’s \(d\)) were calculated to help with the applied interpretation of all \(p\)-values. The magnitude of the effect sizes were interpreted as small (~0.2), medium (~0.5), and large (~0.8) (Cohen, 1988). Bivariate correlations were used to examine linear associations between the dependent variables of interest. An a-priori alpha level of .05 was set for statistical significance. All statistical testing was performed using SPSS version 22 (IBM, Chicago, IL).

**Results**

There were no differences between the groups for body mass and height. People with FAIS were slightly older than the healthy controls (Table 1). Patient reported outcome measures indicated a moderate level of functional limitation and reduced quality of life for people with
FAIS (Table 1). There was no difference in gait speed between the FAIS and healthy control group (FAIS 1.37 ± .12 vs. Control 1.38 ± .16, p = .799).

Isometric hip flexion muscle strength did differ between groups; hip flexion muscle strength was significantly lower in people with FAIS than the control group. The magnitude of the difference in hip flexion muscle strength was medium. However, isometric hip abduction muscle strength did not differ between groups (Table 2).

There were no significant correlations between isometric strength measures and either peak hip joint moments during gait or PROs in the FAIS group (Table 3) (Figure 4 A&B).

Table 1. Demographics for people with FAI syndrome and healthy controls (n =40)

<table>
<thead>
<tr>
<th></th>
<th>FAIS</th>
<th>Control</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>10 M/10F</td>
<td>10 M/10F</td>
<td>--</td>
</tr>
<tr>
<td>Age</td>
<td><strong>25.3 (7.5)</strong></td>
<td><strong>21.3 (2.4)</strong></td>
<td><strong>.031</strong></td>
</tr>
<tr>
<td>Weight</td>
<td>74.6 (16.3)</td>
<td>72.2 (14.4)</td>
<td>.624</td>
</tr>
<tr>
<td>Height</td>
<td>174.0 (9.5)</td>
<td>173.8 (11.9)</td>
<td>.961</td>
</tr>
<tr>
<td>Hip Outcome Score (n=20)</td>
<td>70.7 (12.5)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Nonarthritic Hip Score (n=20)</td>
<td>63.9 (14.8)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>International Hip Outcome Tool (n=14)</td>
<td>46.7 (16.7)</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Bold** p-value indicates statistical significance of p < .05

Table 2. Isometric hip muscle strength (N·m·kg⁻¹) and hip joint kinetics (N·m·kg⁻¹) during gait for people with FAIS and healthy controls.

<table>
<thead>
<tr>
<th></th>
<th>FAIS</th>
<th>Control</th>
<th>p-value</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip Strength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td><strong>1.1 (.33)</strong></td>
<td><strong>1.5 (.25)</strong></td>
<td><strong>.001</strong></td>
<td><strong>.56</strong></td>
</tr>
<tr>
<td>Abduction</td>
<td>1.5 (.45)</td>
<td>1.7 (.32)</td>
<td>.12</td>
<td>.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>FAIS</th>
<th>Control</th>
<th>p-value</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip Kinetics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Flexion</td>
<td>1.00 (.19)</td>
<td>1.03 (.22)</td>
<td>.67</td>
<td>.15</td>
</tr>
<tr>
<td>Peak Abduction</td>
<td>-.96 (.23)</td>
<td>-.94 (.19)</td>
<td>.76</td>
<td>.09</td>
</tr>
</tbody>
</table>

**Bold** p-value indicates statistical significance of < .05
The purpose of this study was to investigate the role of hip flexion and abduction muscle strength in relation to quantitative and qualitative measures of function in people with FAIS. We hypothesized that people with FAIS would demonstrate less hip flexion and abduction muscle strength when compared to healthy controls, and that the extent the hip muscle strength loss would correlate with peak hip kinetics during gait and with PROs in people with FAIS. First, our findings partially support our initial hypothesis in that people with FAIS exhibited significantly less hip flexion muscle strength than healthy controls. Contrary to these hypotheses, however, no group differences in hip abduction muscle strength was found, and no significant correlations existed between hip muscle strength measures and either peak hip joint moments during gait or PROs in the FAIS group. The results of this study therefore suggest that while strength of certain muscle groups are impaired in people with FAIS, this impairment does not appear to be related to the quantitative measure of biomechanical hip joint function or qualitative measures of patient reported outcomes.

Table 3. Correlations (Pearson’s r) between hip strength, hip kinetics, and patient reported outcomes in people with FAIS.

<table>
<thead>
<tr>
<th></th>
<th>Flexion Strength</th>
<th></th>
<th>Abduction Strength</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>p-value</td>
<td>R</td>
<td>p-value</td>
</tr>
<tr>
<td><strong>Hip Kinetics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Flexion Moment</td>
<td>.031</td>
<td>.829</td>
<td>.147</td>
<td>.337</td>
</tr>
<tr>
<td>Peak Abduction Moment</td>
<td>.168</td>
<td>.479</td>
<td>.077</td>
<td>.746</td>
</tr>
<tr>
<td><strong>Patient Reported Outcomes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HOS-ADL</td>
<td>-.007</td>
<td>.977</td>
<td>.203</td>
<td>.391</td>
</tr>
<tr>
<td>NAHS</td>
<td>.225</td>
<td>.339</td>
<td>.197</td>
<td>.405</td>
</tr>
<tr>
<td>iHot 33</td>
<td>.081</td>
<td>.767</td>
<td>.348</td>
<td>.187</td>
</tr>
</tbody>
</table>
Figure 4. Sagittal (A) and frontal (B) plane joint moments during gait in people with FAIS (dark grey dot) and healthy controls (black solid). Note: Positive values indicate hip flexion and hip adduction joint moments, whereas negative values indicate hip extension and hip abduction joint moments.

In the current study, isometric hip flexion muscle strength was 31% lower in people with FAIS compared to healthy controls. This difference in muscle strength is consistent with the 28% decrement in flexion strength in people with FAIS that was reported by other authors (N.)
Casartelli et al., 2011). Although the current study did not find any association between hip flexion strength and peak hip flexor moments during gait in persons with FAIS, there may still be a functional significance to this muscle weakness that was not detected in the current investigation. Perhaps the functional significance of hip flexion muscle strength impairment can be drawn from previous musculoskeletal modelling studies. In simulation based modelling studies, iliopsoas muscle weakness can only be tolerated to a limited extent, and ultimately leads to compensations in force output by other muscles to maintain normal gait kinematics (van der Krogt, Marjolein M et al., 2012). The lack of difference in peak hip flexion moments between the groups in the current study indicates that joint-based gait kinetics were similar between groups, which is consistent with previous findings (L. E. Diamond et al., 2016; Kennedy et al., 2009; Samaan et al., 2016). Perhaps a clinical consideration not immediately apparent arises if one considers the strength and kinetic data in combination during prolonged activity. For example, while the similarity in peak hip kinetics during gait indicates that both groups could sufficiently meet the functional demand imposed by the task, the FAIS group appears to operate at a much greater relative level with respect to their peak hip flexion moment (i.e. maximal capacity). Van der Krogt and colleagues showed that a 40% decrease in iliopsoas muscle strength can significantly increase the overall muscle energetic cost of all hip muscles, which arguably could result in an earlier onset of muscle fatigue during prolonged walking (van der Krogt, Marjolein M et al., 2012). Therefore, during prolonged activities, functioning at a higher percentage of maximum capacity may result in muscular compensations and alterations in joint contact forces, which may explain the development of anterior hip pain during prolonged walking as reported by people with FAIS (Clohisy et al., 2009). Another consideration is that the peak hip flexion moment occurs when the hip is in a position of maximal extension during gait (~ 10 degrees). Interestingly, another modelling study found that a combination of iliopsoas weakness with the hip in a position of 10 degrees of extension results in large anteriorly directed hip joint forces, which could also exacerbate symptoms in persons with FAIS during prolonged walking activity.
(Lewis, Sahrmann, & Moran, 2007). However, more research is needed to directly investigate hip joint contact forces in people with FAIS during gait to better understand the symptoms of FAIS and potential disease progression.

The lack of difference in hip abduction muscle strength was an unexpected. First, the observed lack of differences in hip abduction strength between people with FAIS and healthy controls is not consistent with previous studies (N. Casartelli et al., 2011; Harris-Hayes et al., 2014). A possible explanation for this discrepancy may be related to the isometric strength testing position. We tested hip abduction muscle strength in a neutral position, whereas previous investigators used various positions of hip abduction (N. Casartelli et al., 2011; Harris-Hayes et al., 2014). However, the greatest amount of force production for hip abduction occurs in a near neutral abduction position, which may perhaps limit the likelihood of detecting any differences in hip muscle strength, when compared to testing at the near end range position of hip abduction (Harris-Hayes et al., 2014; Neumann, Soderberg, & Cook, 1988). The other explanation for the discrepancy between our findings and those of others could be due to slight differences in patient populations. For example, Harris-Hayes and colleagues (2014) tested hip abduction strength in a mixed population with not only FAIS, but also acetabular dysplasia, hip instability, and isolated acetabular labral tears in the absence of FAI (Harris-Hayes et al., 2014). Therefore, it could very well be that people in that study simply generated less hip abductor force near end ranges of hip motion because of pain or apprehension.

It is interesting that hip flexion or abduction strength were not correlated with the HOS-ADL, NAHS, and iHot 33 questionnaires in people with FAIS. Perhaps the reason for the lack of associations is that the qualitative patient reported outcomes are very broad and assess, and assess activities that require low levels of muscle function. In addition, clearly muscle strength may have no bearing on certain domains of the iHot 33, such as the social, emotional, and lifestyle domains, which may be the reason for the lack of association between this PRO and hip muscle strength.

From a functional performance perspective, perhaps our results indicate that people with FAIS
have sufficient hip strength to tolerate the activity demands measured by the HOS-ADL and NAHS. Perhaps, the use of a PRO that assesses function during higher level activities such as sports participation may be more appropriate to examine this type of association. Additionally, previous studies on hip pathology that have shown associations between muscle strength and PROs have correlated the change in these variables across time as opposed to at a single cross-sectional time point. Therefore, further research is needed to prospectively analyze whether strength changes in FAIS are directly associated with change in patient reported function.

The current study is not without limitations. First, people with FAIS were not subcategorized based on type of FAI morphology, which limits any insight into morphology-dependent differences in gait kinetics. However, the inclusion criteria for the FAIS group in the current study (e.g., positive intra-articular injection test) were very stringent. In addition, the use of patient questionnaires arguably helped to appropriately characterize the sample of people with FAIS. Second, walking may not be a demanding enough task to elicit biomechanical differences in people with FAIS group when compared to healthy controls. Future studies should analyze tasks with greater demands on the hip joint, which may provide more insight into how FAIS may impact hip joint biomechanics during function. Similarly, investigations that focus on the effects of prolonged activity may provide additional understanding on how people with FAIS cope with changing functional demands of an activity over an extended period. Lastly, our interpretations about the role of muscle strength in relation to joint kinetics are an oversimplification, because they ignore muscle force-velocity and length-tension properties as well as the passive forces that may contribute to peak hip flexion moments during gait. Therefore, future studies should account for these muscle properties to better understand the role of reduced hip muscle strength and its potential implications on prolonged functional activity.
III. BIOMECHANICAL HIP JOINT FUNCTION IS ALTERED IN PEOPLE WITH FEMOROACETABULAR IMPINGEMENT SYNDROME WHEN THE JOINT CONTROL DEMANDS ARE PROGRESSED FROM A DOUBLE TO SINGLE LEG SQUAT TASK

Introduction

Femoroacetabular impingement syndrome (FAIS) is a clinical hip disorder that represents the symptomatic contact between the femur and/or acetabulum during the relative extremes of hip motion (Ganz et al., 2003; Griffin et al., 2016). FAIS has been linked to acetabular labral tears, articular cartilage injury, and has been implicated in the development of secondary hip osteoarthritis (Agricola et al., 2013; Beck et al., 2005; Bedi & Kelly, 2013). FAIS typically presents in young individuals and active adults, and is characterized by hip pain, loss of hip flexion and internal rotation range of motion, and the reproduction of symptoms during impingement testing (Clohisy et al., 2009; L. E. Diamond et al., 2015; Gerhardt et al., 2012; Griffin et al., 2016; Kapron et al., 2011; Nepple, Brophy, Matava, Wright, & Clohisy, 2012; Philippon et al., 2007). However, little evidence exists on how FAIS may impact hip joint biomechanics during dynamic functional activities. The investigation of hip joint biomechanics during functional tasks could help improve the treatment of FAIS through a better understanding of hip joint movement compensations, which are common to these patients.

Double- and single-leg squats are tasks that are integral to many sport and activities performed by young individuals and active adults, but could also exacerbate pain in people with FAIS (Clohisy et al., 2009; L. E. Diamond et al., 2015; Philippon et al., 2007). It has been suggested that a double leg squat is a useful functional activity to assess movement in persons with FAIS because it may bring about compensations in movement associated with FAIS symptoms (Lamontagne et al., 2009). Recent studies have shown alterations in hip joint biomechanics during a double leg squat task (Bagwell et al., 2016; L. Diamond et al., 2017; Lamontagne et al., 2011). The most recent evidence suggests that constraining kinematic
parameters of the squat task, such as pelvic and trunk position, may better expose biomechanical alterations during a double leg squat task in persons with FAIS (L. Diamond et al., 2017).

Another way to constrain aspects of the movement strategy during a squat task is to progress the squat from double to single leg, which inherently changes the joint control demands of the task. Interestingly, a previous study in people with hip chondropathy demonstrated impairments in single leg balance control, although, some of these individuals had hip disorders other than FAIS (Hatton, Kemp, Brauer, Clark, & Crossley, 2014). To that end, no study has investigated biomechanical hip joint function in people with FAIS during a single leg squat task. Additionally, the investigation of whether hip biomechanics are impaired more so during a squat task that requires greater hip joint control, may help to expose biomechanical compensation inherent to people with FAIS.

A better understanding of hip joint biomechanical function in people with FAIS during squat tasks will help inform rehabilitation interventions by providing specific targets for treatment related alterations in hip joint control. The purpose of this study is to determine if hip joint biomechanical differences between people with FAIS and healthy controls are influenced by the joint control demands of the squat task. We hypothesize that differences in hip joint biomechanics between people with FAIS and healthy controls will be influenced by the joint control demands of the task such that single leg squat task will reveal greater differences in hip joint biomechanics between the groups.

**Methods**

**Study Design**

The current study was a cross-sectional, case-controlled design with two independent variables. The first independent variable was GROUP with two levels: people with FAIS and healthy matched controls. The second independent variable was TASK which represents two
levels of joint control: double-leg squat and single-leg squat. The hip joint kinematic and kinetic
dependent variables of interest were: peak hip flexion angle, peak hip internal rotation angle, peak
hip adduction angle, peak hip extension moment, peak hip abduction moment, and peak hip
external rotation moment. The dependent variables associated with squat performance were: squat
depth, cycle duration, mean center of mass (CoM) descent velocity, and mean CoM ascent
velocity.

Participants

Previous studies have demonstrated differences in peak hip flexion angles, peak hip
extension moments, peak hip internal rotation angle, and squat depth during a double-leg squat
task in people with FAIS when compared to healthy controls, therefore only these variables were
considered when calculating the sample size required for this study (Bagwell et al., 2016;
Lamontagne et al., 2009). The a priori sample size calculation revealed that a total of 26
participants were needed to achieve 90% statistical power at an α-level of 0.05 for the mixed-
model statistical design. As such, 14 people with FAIS and 14 healthy controls, who were
matched for gender, body mass, and height, were recruited for this study (Table 4). All
participants were between the ages of 14 – 40 (24.4± 6.4) years old.

All participants with FAIS were diagnosed by a single orthopedic surgeon who
specializes in the treatment of FAIS. A positive diagnosis of FAIS required all of the following
criteria: 1) hip pain ≥ 3 months; 2) a positive anterior impingement (FADIR) test; 3) radiographic
evidence of FAI defined by any of the following: alpha angle >55° (cam type); center edge angle
>40° (pincer type); or confirmed crossover sign (pincer type); 4) Tonnis grade ≤ 1 on standard
radiograph; 5) magnetic resonance imaging with no evidence of diffuse articular cartilage
degeneration; 6) positive response to an intra-articular anesthetic injection, which was defined as
the temporary pain relief during impingement testing immediately following the injection.
General exclusion criteria for both FAIS and healthy control participants included: report of low back or lower extremity injury within the last 6 months, history of hip fracture or dislocation, previous diagnosis of any developmental hip conditions, and any systemic disorders that limit the performance of activities of daily living.

Table 4. Mean(SD) demographics for people with FAIS and controls (n=28).

<table>
<thead>
<tr>
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<th>FAIS (n=14)</th>
<th>Control (n=14)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender (n)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Female</td>
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<td>7</td>
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</tr>
<tr>
<td>Age (years)</td>
<td>28 (7)</td>
<td>21 (1)</td>
<td>.0001*</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.7 (1.1)</td>
<td>1.7 (1.2)</td>
<td>0.87</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>76.3 (18.2)</td>
<td>71.3 (15.5)</td>
<td>0.44</td>
</tr>
</tbody>
</table>

* indicates statistical significance (p < .001)

Healthy, active control participants were recruited from a general university population. The participants were matched for gender, body mass, and height. A physical screening examination was performed on all control participants to rule out potential cam or pincer type morphology. The screening examination was performed by a single licensed physical therapist with over 13 years of clinical experience (PM). The screening examination consisted of passive range of motion measurements and a physical examination. Because the limitation of hip internal rotation at 90° of flexion has been associated with FAI morphology and hip osteoarthritis in otherwise healthy individuals, this clinical measure was used to assist in ruling out potential underlying asymptomatic FAI (Bedi & Kelly, 2013; Neppe et al., 2013). Limited hip flexion was defined as < 85°, and limited internal rotation at 90° of hip flexion was defined as < 10° of internal rotation. The physical examination consisted of the anterior impingement test (FADIR test), FABER test, log roll test, and the dial test (Byrd, 2007; Clohisy et al., 2009; Philippon et al., 2007). Participants were excluded if any examination technique elicited anterior groin or lateral hip pain, or met the pre-determined range of motion limitation cutoffs.
Squat Task Data Acquisition

A 14-camera motion analysis system (Vicon Motion Systems Ltd. London, UK) was used to sample kinematic data at 100 Hz. Forty-five retro-reflective markers were attached to the anatomic landmarks by a single investigator (PM) for all participants. Single markers were attached to the: C7 spinous process, T10 spinous processes, sternum, and bilaterally over the posterior superior iliac spine, anterior superior iliac spines, iliac crests, greater trochanters, medial and lateral knee joint lines, medial and lateral malleoli, and first and fifth metatarsal heads. In addition, marker clusters, which consisted of 4 markers each, were attached to the bilateral thighs and shanks, and clusters of 3 markers each were fixed to the bilateral heels of the participants. A static standing trial with all markers was collected to define segment parameters and to estimate joint center locations. Then all single markers were removed, except those on the pelvis and trunk and marker clusters leaving 29 markers for movement testing. Three-dimensional ground reaction force and moment data were sampled at 1000 Hz with two in-ground AMTI force plates (AMTI Corp. Watertown, MA, USA).

A double- and single-leg squat were chosen because both tasks involve kinematic patterns that require near end ranges of hip motions, which would reproduce symptomatic impingement and pain in people with FAIS. In addition, a single leg squat task requires an inherently greater joint control demand than a double leg squat task, and introduces a degree of constraint to the task. All double- and single-leg squats were performed at self-selected speeds to be more representative of functional movement evaluations used in the clinical setting. The instructions provided to participants were, “squat as low as possible while keeping your feet or foot firmly in contact with the force plate(s) at all times.” The lack of use of a depth target was chosen to promote the use of everyone’s self-selected movement strategy and account for individual differences in range of motion, especially in the FAIS population.
The double-leg squat task consisted of participants standing with each foot on a force plate at a shoulder width distance and toes pointing forward (Figure 5). The single-leg squat task consisted of participants standing on a force plate with the stance limb toes pointing forward and with the non-stance limb held so that the knee was flexed to a comfortable position and the non-stance thigh remained either in line with or behind the squat leg during the movement (Figure 6).

To provide a standard upper extremity position during both squat tasks, participants raised their arms to shoulder height such that the finger tips were pointing forward and palms facing the floor. Participants performed five successful double-leg and single leg squats to maximal depth. A successful trial was defined as a squat in which the participant’s feet remained completely in contact with the force plate(s) throughout the movement, maintained stable balance without shifting the stance foot on the plate, and avoided touching the non-stance foot to the ground. Participants were given 30 seconds between each squat to prevent lower extremity fatigue and no more than 6 trials were collected per leg to avoid fatigue.

Figure 5. Example of the double leg squat task.
Figure 6. Example of the single leg squat task.

**Squat Task Data Processing**

Kinematic and kinetic data were processed with Visual 3D software (C-Motion, Inc, Rockville, MD, USA). Kinematic and kinetic data were filtered with a 4th order, low-pass Butterworth filter using a cutoff frequency of 6 Hz. A hybrid link segment model was built using the CODA pelvis (Charnwood Dynamics Ltd. Leicestershire, UK). A joint coordinate system approach was used to calculate joint angles at the hip (Spoor & Veldpaus, 1980). An inverse dynamics approach was used to calculate the net joint moments using the distal relative to the proximal segment. All joint moments are reported as internal moments and were normalized to body mass (N·m·kg⁻¹). The peak value for each joint kinematic and kinetic variable was extracted from each non-time normalized series for all successful trials of each task. A five-trial ensemble average of the peaks was then calculated and used for further analysis.

**Squat Task Data Analysis**

Given that it is common for people with unilateral FAIS to demonstrate radiographic evidence of cam or pincer FAI morphology in the contralateral hip, despite lack of clinical symptoms on the contralateral side, only data from the involved hip were analyzed and matched to the dominant leg of all controls (Allen, Beaule, Ramadan, & Doucette, 2009; Klingenstein,
Zbeda, Bedi, Magennis, & Kelly, 2013). A custom written MATLAB program was used to identify the start and end of the squat cycle, and to time normalize this cycle to 101 data points. The center of mass (CoM) of the model was calculated based on a weighted average of all the masses of the kinetic segments included in the model (i.e. segments used in inverse dynamic calculations). The CoM was a virtual point located within the center of the pelvis segment based on the segments contained in the model. The squat cycle start, and end were defined when the CoM vertical position was 3 standard deviations away from the quiet stance CoM vertical position. Squat depth was defined as the change in CoM position from quiet stance to the minimum vertical position during the squat cycle. The squat cycle was broken into a descent phase, which was from the beginning of the squat cycle to minimum vertical CoM distance, and ascent phase, which was defined from minimum vertical CoM position to the end of the squat cycle. The first-time derivative of CoM position was calculated and used to determine CoM velocity during the descent and ascent phases of the squat cycle. The average CoM velocity was calculated for each phase of the squat cycle during each trial. A five-trial ensemble average was calculated for each squat performance variable.

**Statistical Analysis**

Prior to statistical analysis all data were screened to determine if parametric statistical testing was appropriate. Box plots were first inspected for all dependent variables to evaluate for outliers within the data. The Shapiro-Wilk’s test of normality was performed to ensure all data were normally distributed. Levene’s test was used to ensure homogeneity of variance, whereas Box’s test was used to evaluate the equality of covariance matrices as necessary for repeated measures analysis.

Independent samples t-tests were used to assess between-group differences in age, body mass and height to ensure that the groups were appropriately matched. Two-way mixed model ANOVAs were used to determine if there were significant differences between GROUPS (FAIS...
and control) and TASK (two types of squat) for any of the dependent variables of interest. Follow-up post hoc analyses were performed for variables with a significant GROUP by TASK interaction. The post-hoc analysis consisted of independent samples t-tests to evaluate GROUP differences at each level of TASK, and paired samples t-tests were used to evaluate TASK difference within each GROUP. An a-priori α-level of 0.05 was used as the threshold for statistical significance testing. All statistical testing was performed using SPSS version 22 (IBM, Chicago, IL, USA).

Results

There was a significant GROUP by TASK interaction for peak hip adduction angle (Table 5: $F_{(1,26)} = 6.958, P = 0.014, \eta^2 = 0.211$). Main effects of TASK were noted for both peak hip flexion ($F_{(1,26)} = 75.292, P = 0.001, \eta^2 = .743$) and peak hip internal rotation angle ($F_{(1,26)} = 6.667, P = 0.016, \eta^2 = 0.204$) (Table 5).

Post hoc analyses for peak hip adduction angle revealed that compared to healthy controls people with FAIS demonstrated significantly smaller peak hip adduction angles during the single-leg squat ($P = .03$) but not the double-leg squat task ($P = .68$) (Figure 7). Within-group differences in peak hip adduction angle were observed for both the FAIS ($P = 0.001$) and control group ($P = 0.001$) regardless of TASK.
Table 5. Mean (SD) peak hip flexion angle (Pk. Flex), peak hip internal rotation angle (Pk. IR), and peak hip adduction angle (Pk. Add) for double-leg (DBL) and single-leg (SING) squat.

<table>
<thead>
<tr>
<th></th>
<th>FAIS</th>
<th>Control</th>
<th>Interaction</th>
<th>Group</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DBL</td>
<td>SING</td>
<td>DBL</td>
<td>SING</td>
<td>P</td>
</tr>
<tr>
<td>Pk. Flex (°)</td>
<td>104.0</td>
<td>85.7</td>
<td>106.1</td>
<td>94.7</td>
<td>.05</td>
</tr>
<tr>
<td></td>
<td>(5.8)</td>
<td>(10.2)</td>
<td>(11.8)</td>
<td>(13.1)</td>
<td></td>
</tr>
<tr>
<td>Pk. IR (°)</td>
<td>9.2</td>
<td>4.6</td>
<td>12.7</td>
<td>7.0</td>
<td>.79</td>
</tr>
<tr>
<td></td>
<td>(8.4)</td>
<td>(8.2)</td>
<td>(7.5)</td>
<td>(6.2)</td>
<td></td>
</tr>
<tr>
<td>Pk. Add (°)</td>
<td>-4.3</td>
<td>10.2</td>
<td>-4.7</td>
<td>15.8</td>
<td>.01</td>
</tr>
<tr>
<td></td>
<td>(2.5)</td>
<td>(4.3)</td>
<td>(2.5)</td>
<td>(8.0)</td>
<td></td>
</tr>
</tbody>
</table>

Bold indicates significant GROUP*TASK interaction (p < .05)
* indicates significant main effect (p < .05)
ES = effect size (η²)

Note: Positive values for joint angles indicate flexion, adduction, and internal rotation.
Negative values for joint angles indicate extension, abduction, and external rotation.
There was a significant GROUP by TASK interaction for peak hip extension (Table 6: $F_{(1,26)} = 6.611, P = 0.016, \eta^2 = 0.203$) and peak hip abduction moment ($F_{(1,26)} = 11.591, P = 0.002, \eta^2 = 0.308$). A main effect for TASK was observed for peak hip external rotation moment ($F_{(1,26)} = 129.541, P = 0.005, \eta^2 = .833$).

Table 6. Mean (SD) peak hip extension (Pk. Ext), peak hip external rotation (Pk. ER), and peak hip abduction (Pk. Abd) moment (N·m·kg$^{-1}$) for double-leg (DBL) and single-leg (SING) squat.

<table>
<thead>
<tr>
<th></th>
<th>FAIS</th>
<th>Control</th>
<th>Interaction</th>
<th>Group</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DBL SING</td>
<td>DBL SING</td>
<td>P ES</td>
<td>P ES</td>
<td>P ES</td>
</tr>
<tr>
<td>Pk. Ext</td>
<td>-1.0 -.14</td>
<td>-1.2 -.08</td>
<td>.02 .002</td>
<td>.003*</td>
<td>.001*</td>
</tr>
<tr>
<td></td>
<td>(.2) (.12)</td>
<td>(.2) (.07)</td>
<td>.203 .308</td>
<td>.299</td>
<td>.594</td>
</tr>
<tr>
<td>Pk. ER</td>
<td>-.18 .82</td>
<td>-.52 -.08</td>
<td>.40 .08</td>
<td>.64</td>
<td>.009</td>
</tr>
<tr>
<td></td>
<td>(.12) (.28)</td>
<td>(.17) (.07)</td>
<td>.028 .08</td>
<td>.009</td>
<td>.833</td>
</tr>
<tr>
<td>Pk. Abd</td>
<td>-1.3 -.08</td>
<td>-2.0 -1.10</td>
<td>.002 .002</td>
<td>.08</td>
<td>.915</td>
</tr>
<tr>
<td></td>
<td>(.6) (.2)</td>
<td>(.5) (.13)</td>
<td>.299 .308</td>
<td>.113</td>
<td>.915</td>
</tr>
</tbody>
</table>

**Bold** indicates significant GROUP*TASK interaction (p < .05)
* indicates significant main effect (p < .05)
ES = effect size ($\eta^2$)

Note: Positive values for joint angles indicate flexion, adduction, and internal rotation. Negative values for joint angles indicate extension, abduction, and external rotation.
Post hoc analyses of peak hip extension moments showed that people with FAIS demonstrate significantly smaller peak hip extension moments than healthy controls during both a double- \( (P = .03) \) and single-leg squat task \( (P = .004) \) (Figure 8). Within group differences for task were also observed for both the FAIS \( (P = .04) \) and control group \( (P = .0001) \) for peak hip extension moments.

Similarly, post hoc analysis of peak hip abduction moments demonstrate that people with FAIS also exhibit lower peak hip abduction moments during a single leg squat task compared to healthy controls \( (P = .01) \). However, no difference was observed between the groups for the double leg squat task \( (P = .08) \) (Figure 9). Within group differences for task were observed for both the FAIS \( (P = .0001) \) and control group \( (P = .0001) \). These results also indicate that the single leg squat task required a significantly greater demand on the hip abductors than a double leg squat task.
Figure 8. Sagittal plane hip moment waveforms during a double (A) and single leg (B) squat task in people with FAIS (dark grey dot) and healthy controls (black solid).
B.

Figure 9. Frontal plane hip moment waveforms during a double leg (A) and single leg (B) squat task in people with FAIS (dark grey dot) and healthy controls (black solid).

There were significant GROUP main effects for total squat cycle duration (Table 7: $F_{(1,26)} = 5.220, P = 0.031, \eta^2 = 0.167$), squat descent velocity ($F_{(1,26)} = 8.397, P = 0.008, \eta^2 = 0.244$) and squat ascent velocity ($F_{(1,26)} = 8.067, P = 0.009, \eta^2 = 0.237$). The FAIS group squatted with slower velocities than the control group (Figure 10) and demonstrated a longer squat cycle duration than the controls. Significant main effects were also observed for TASK for squat depth ($F_{(1,26)} = 113.510, P = 0.001, \eta^2 = 0.814$), squat cycle duration ($F_{(1,26)} = 4.781, P = 0.038, \eta^2 = 0.155$), squat descent velocity ($F_{(1,26)} = 30.679, P = 0.001, \eta^2 = 0.541$) and squat ascent velocity ($F_{(1,26)} = 26.348, P = 0.001, \eta^2 = 1.503$).
Table 7. Mean (SD) for squat depth (m), descent velocity (m·s$^{-1}$), ascent velocity (m·s$^{-1}$), and cycle duration (sec.) for double-leg (DBL) and single-leg (SING) squats.

<table>
<thead>
<tr>
<th>Group</th>
<th>Task</th>
<th>FAIS</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DBL</td>
<td>SING</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBL</td>
<td>SING</td>
</tr>
<tr>
<td>Depth</td>
<td>.46</td>
<td>.47</td>
<td>.25</td>
</tr>
<tr>
<td></td>
<td>(.11)</td>
<td>(.13)</td>
<td>(.08)</td>
</tr>
<tr>
<td>Descent velocity</td>
<td>-.28</td>
<td>-.39</td>
<td>-.17</td>
</tr>
<tr>
<td></td>
<td>(.10)</td>
<td>(.17)</td>
<td>(.06)</td>
</tr>
<tr>
<td>Ascent velocity</td>
<td>.37</td>
<td>.47</td>
<td>.24</td>
</tr>
<tr>
<td></td>
<td>(.13)</td>
<td>(.16)</td>
<td>(.07)</td>
</tr>
<tr>
<td>Duration</td>
<td>3.13</td>
<td>2.36</td>
<td>2.57</td>
</tr>
<tr>
<td></td>
<td>(.86)</td>
<td>(.63)</td>
<td>(.77)</td>
</tr>
</tbody>
</table>

* indicates significant main effect (p < .05)
ES = effect size ($\eta^2$)
Discussion

The purpose of the current study was to determine if hip joint biomechanical differences between people with FAIS and healthy controls are influenced by the joint control demands of a squat task. We hypothesized that differences in hip joint biomechanics between people with FAIS and healthy controls will be influenced by the joint control demands of the task such that single leg squat task will reveal greater differences in hip joint biomechanics between the groups. Our findings indicate differences in hip joint biomechanics between people with FAIS and healthy controls and that these differences are influenced by the control demand of the squat task. These results support our hypothesis that a single leg squat would elicit greater differences in hip joint kinematics and kinetics between people with FAIS and healthy controls. The clinical implications of these results are that a single-leg squat is more likely to expose movement compensations in people with FAIS and may thus serve as a better tool to evaluate functional movement patterns.

Figure 10. CoM velocity during a double and single leg squat task in people with FAI syndrome (dark grey dot) and healthy controls (black solid)
in this population. Additionally, the biomechanical compensation revealed during the squat tasks provide rationale for targeting rehabilitation strategies at sagittal and frontal plane muscle groups to address the control demands in these planes.

Double- and single-leg squats require a considerable hip extensor moment to control the sagittal position of the trunk and upper-body during the descent and ascent phases (Graci, Van Dillen, & Salsich, 2012; Nakagawa, Moriya, Maciel, & Serrão, 2012). Our results (i.e., GROUP by TASK interaction) indicate that as all participants switched from double- to single-leg squats, people with FAIS did not increase peak hip extensor moments as the healthy controls did, despite the inherently greater sagittal plane control demand. Furthermore, the post hoc analysis results indicate that people with FAIS demonstrated smaller peak hip extensor moments than controls regardless of task. These results are consistent with those from a recent study that also showed that people with cam impingement (i.e., a type of FAIS) exhibit lower mean hip extensor moments during a double-leg squat task compared to healthy controls, and are the first to reveal biomechanical alterations in people with FAIS during a single leg squat task (Bagwell et al., 2016). Collectively, the current findings and that of previous studies, suggest that people with FAIS adopt a movement strategy that is characterized by an overall lower contribution from the hip extensor muscles and a comparatively smaller increase in hip extensor moments as the joint control demand increases. Such a strategy would likely help limit, or avoid, pain associated with tasks that require end ranges of hip motion (i.e., during both types of squat) and in situations where hip forces become excessively high (i.e., during single-leg squats).

The frontal plane kinetic differences identified in the current study further support the notion that people with FAIS tend to adopt a hip joint biomechanical strategy associated with less hip joint loading. To elaborate, the results of the current study indicated that frontal plane kinetics in people with FAIS and healthy controls differed only when the joint control demands of the task were progressed from a double to single leg squat. Post-hoc analyses further indicated that people with FAIS demonstrated smaller peak hip abduction moments during the single-leg squat task.
Single-leg squats impose considerable joint control demands on the hip abductor muscles in order to maintain frontal plane stability during the movement (Earl, Monteiro, & Snyder, 2007; Nakagawa et al., 2012). Additionally, the forces produced by the hip abductors during activities that require single-leg stance contribute a considerable amount to the overall hip joint force magnitude (Bergmann et al., 2001; Boudreau et al., 2009; Correa, Crossley, Kim, & Pandy, 2010; Heller et al., 2001; van der Krogt, Marjolein M et al., 2012). Given that the frontal plane control demand during a double leg squat is much less than that of a single leg squat, it is not surprising that a single-leg squat should expose differences in frontal plane kinetics. Again, this finding may represent a strategy to help limit, or avoid, pain associated with tasks that combine end ranges of hip motion and high hip joint forces.

The frontal plane kinematic findings from the current study also agree well with the kinetic findings, and are like other studies (Bagwell et al., 2016). Both groups performed the double-leg squats with modest amounts of hip abduction, which is consistent with a previous study’s findings (Bagwell et al., 2016). But, a statistical interaction between GROUP and TASK for peak hip adduction angles further indicated that while both groups exhibited similar frontal plane hip angles during the double-leg squat, people in the FAIS group did not increase the amount of hip adduction to the same extent as the control group when they performed single-leg squats. Post hoc analysis of peak hip adduction angles confirmed that people with FAIS do demonstrate less peak hip adduction during the single but not double leg squat task. Hip adduction can result in abnormal hip joint contact and pain in people with FAIS, especially during motions that also include combinations of hip flexion and internal rotation (Bedi & Kelly, 2013; Griffin et al., 2016). Given that a single-leg squat combines these motions it is not surprising that people with FAIS would exhibit limited hip adduction to avoid positions that produce abnormal hip contact and pain.

It is noteworthy that while several of the hip joint kinematic and kinetic data in the current study were subject to statistical interactions, group differences in squat performance
variables between people with FAIS and healthy controls did not differ based on the control demands of the tasks. This is somewhat surprising because of the apparent differences in the base of support and frontal plane control demands between the single-leg and double-leg squat. The results, however, did indicate that squat descent velocity and ascent velocity were slowed, and squat cycle duration was longer in the FAIS group than the control group. These differences indicate that people with FAIS do exhibit a different strategy to control movement than otherwise healthy people. Control (i.e., either rising and lowering) of the body’s CoM is a basic requirement for the functional completion of any squat task. Poor, or inadequate, control can adversely influence the magnitude of the hip and knee joint moments (Farris, Lichtwark, Brown, & Cresswell, 2015; Mathiyakom, McNitt-Gray, Requejo, & Costa, 2005). Based on impulse-momentum physics, lengthening the duration of the squat cycle would allow the movement of the CoM to be controlled with less muscular force at the hip. Since smaller muscle forces are related to smaller joint reaction force, the observed reductions in squat velocities likely represent the control parameter of the compensatory strategy that is used to either reduce pain and prevent symptoms at near end ranges of hip motion (Correa et al., 2010; van der Krogt, Marjolein M et al., 2012). The current finding that squat depth did not differ between groups is consistent with a recent study, which examined constrained and unconstrained squat tasks in people with FAIS compared to healthy controls (L. Diamond et al., 2017). However, these findings are inconsistent with two previous studies that examined double-leg squats in a group with cam-type FAI (Bagwell et al., 2016; Kennedy et al., 2009). Perhaps a potential reason for the discrepancy is that previous investigations constrained the temporal duration of the squat cycle, whereas the current study allowed for a self-selected cycle duration during both types of squat.

Several limitations to the current study should be considered when interpreting the findings. First, we acknowledge that the healthy controls, albeit asymptomatic, were not radiographically confirmed to be free of FAI morphology. Previous studies, however, have also only relied on physical exams to exclude control participants with symptoms indicative of
underlying cam or pincer type FAI (Hunt et al., 2013). Another limitation to this study is that trunk kinematics were not considered in the analyses. Including a trunk segment would allow for a more detailed investigation of the relationship between hip joint function of the body’s CoM, which may assist in the interpretation of movement control strategies of people with FAIS. Finally, it is difficult to discern whether the squat-dependent differences in hip biomechanics between the groups reflect a control demand or intensity-dependent compensation in movement pattern.
IV. ARTHROSCOPIC SURGERY FOR FEMOROACETABULAR IMPINGEMENT SYNDROME ALTERS HIP RANGE OF MOTION, MUSCLE STRENGTH, AND SAGITTAL PLANE JOINT KINETICS DURING GAIT

Introduction

Femoroacetabular impingement syndrome (FAIS) is a clinical hip disorder that represents the symptomatic contact between the proximal femur and acetabular rim during hip motion (Griffin et al., 2016). FAIS manifests as a combination of hip symptoms, clinical signs, and imaging findings that indicate boney over-coverage of the hip joint (Bedi & Kelly, 2013; Griffin et al., 2016). A common treatment for FAIS is arthroscopic hip surgery, which has grown exponentially over the last 10 years (Bozic et al., 2013). Patient reported outcomes are most commonly used to measure function after arthroscopic hip surgery for FAIS and short to mid-term follow-up studies have demonstrated significant improvement in these measures (Levy et al., 2016; Menge et al., 2017; Nho et al., 2011). However, little evidence exists on quantitative measures of hip joint function after arthroscopic hip surgery for FAIS (Kierkegaard et al., 2017).

Numerous studies have demonstrated the utility of three-dimensional (3D) motion analysis to quantify hip joint function (Bagwell et al., 2016; Bagwell, Fukuda, & Powers, 2016; L. E. Diamond et al., 2016; Foucher et al., 2007; Hunt et al., 2013; Lamontagne et al., 2009; J. Rylander et al., 2013; J. H. Rylander et al., 2011). However, only a limited number of studies have quantified hip joint function after arthroscopic hip surgery for FAIS (J. Rylander et al., 2013; J. H. Rylander et al., 2011). These studies found that hip kinematics during gait improve after arthroscopic hip surgery as characterized by greater sagittal and transverse plane hip motions (J. Rylander et al., 2013; J. H. Rylander et al., 2011). Although these findings are important to quantify improvement after arthroscopic hip surgery for FAIS, these analyses were limited to kinematic measures of hip joint function. Since mechanical demands on the hip are significant (e.g., compressive forces of about three times body weight during gait), hip joint kinetics should also be considered as an important quantitative measure of hip joint function.
(Bergmann et al., 2001; Correa et al., 2010; Heller et al., 2001). A recent study in people with FAIS found that sagittal plane hip joint impulse is associated with hip joint injury severity and patient reported outcomes (Samaan et al., 2016). These authors suggest that this relationship may imply that hip kinetics represent an important biomechanical parameter for people with FAIS (Samaan et al., 2016). Therefore, the quantification of hip joint function after arthroscopic hip surgery should include both joint kinetic and kinematic measures.

Common clinical signs of FAIS include loss of passive range of hip motion and reduced hip muscle strength (N. Casartelli et al., 2011; N. C. Casartelli et al., 2014; Freke et al., 2016; Griffin et al., 2016; Harris-Hayes et al., 2014; Neppe et al., 2015; Reiman et al., 2017; Tijssen et al., 2016). Despite numerous studies that report improvements in patient reported outcomes after arthroscopic hip surgery, many do not provide quantitative evidence of improvement for clinical measures of joint function, such as hip passive range of motion and muscle strength (Levy et al., 2016; Menge et al., 2017). Quantitative clinical measures, such as passive range of motion and muscle strength, have been shown to be meaningful indicators for the assessment of the disease impact of FAIS, therefore, should also be used to quantify hip joint function after arthroscopic hip surgery for FAIS (Reiman et al., 2017). In addition, these measures are commonly performed in the clinical setting to determine rehabilitation progress and monitor treatment efficacy.

Arthroscopic hip surgery for FAIS involves surgical modification of the joint structure aimed at eliminating symptomatic impingement to improve pain and hip joint dynamics. Therefore, it is important to understand how this surgery impacts the dynamics and function of the hip joint both from a quantitative clinical and biomechanical perspective. Ultimately, this information can be used to identify potential treatment targets and improve clinical decision making based on changes in quantitative measures of hip joint function after arthroscopic hip surgery. The purpose of this study was to determine the effect of arthroscopic hip surgery on clinical and biomechanical measures of hip joint function. We hypothesized that arthroscopic hip surgery in people with FAIS will improve hip joint function, which will be demonstrated by an
increase in hip passive range of motion and hip muscle strength and increases in hip kinematic and kinetic variables.

Methods

Participants

Eight people with FAIS underwent arthroscopic hip surgery, with two of the participants undergoing bilateral surgery approximately 6 months apart. Therefore, data from 10 hips were used for analysis. All FAIS participants completed the Hip Outcome Score, Activity of Daily Living subscale (HOS-ADL) and Nonarthritic Hip Score (NAHS) at the preoperative and postoperative time points. Eight gender, height, and body mass matched healthy controls were included in the analysis. Bilateral data were collected from 2 healthy control participants (i.e. 10 hips). This study was approved by the local university’s institutional review board. All participants provided a written informed consent before participation in the study.

All participants with FAIS were diagnosed by a board certified orthopedic surgeon who specializes in the treatment of hip disorders. The diagnosis of FAIS included the presence of all of the following criterion: 1) hip pain ≥ 3 months; 2) a positive anterior impingement (FADIR) test; 3) radiographic evidence of FAI defined by any of the following criterion: alpha angle >55° (cam type); center edge angle >40° (pincer type); or confirmed crossover sign (pincer type); 4) Tonnis grade ≤ 1 on standard radiograph; 5) magnetic resonance imaging with no evidence of diffuse articular cartilage degeneration; 6) positive response to an intra-articular anesthetic injection, which was defined as the temporary pain relief during impingement testing immediately after the injection. All participants diagnosed with FAIS underwent arthroscopic hip surgery. The arthroscopic hip surgical procedures were specific to the preoperative and postoperative diagnosis. These procedures could include: femoral osteochondroplasty, acetabular
rim trimming, acetabular labral debridement or refixation, microfracture, ligamentum teres debridement and capsular closure.

A convenience sample of healthy control participants were recruited from a general university population, but were matched by gender, body mass and height. A physical screening examination was performed on all healthy control participants to rule out potential cam or pincer FAI morphology. The screening examination was performed by a single licensed physical therapist (PM) with > 14 years’ experience treating FAI and consisted of passive range of motion measurement and a hip joint physical examination. Because limitation of hip internal rotation at 90° of hip flexion has been associated with cam and pincer morphology, and hip OA in otherwise healthy individuals, this clinical measure was used to assist in ruling out potential underlying asymptomatic FAI (Bedi & Kelly, 2013; Neppe et al., 2013). Limited hip flexion was defined as < 85°, and limited internal rotation at 90° of hip flexion was defined as < 10°. The physical examination consisted of the anterior impingement test (FADIR test), FABER test, Log roll test, and the dial test (Byrd, 2007; Ganz et al., 2003; Griffin et al., 2016; Leunig, Beaulé, & Ganz, 2009; Martin et al., 2010; Philippon et al., 2007). Participants were excluded if any examination technique elicited hip pain, and/or met the pre-determined range of motion limitation cutoffs. Control participants were also excluded if they reported any of the following: (1) pain at any other lower extremity joint, (2) low back or lower extremity injury within the last 6 months, (3) history of hip fracture or dislocation, (4) previous diagnosis of any developmental hip conditions, and (5) any systemic disorders that limit the performance of activities of daily living and (6) history of lower extremity surgery of any kind.

Gait Data Acquisition

Forty-five retroreflective markers were attached to anatomic landmarks. Three-dimensional position data of these reflective markers were collected at 100Hz with a 14-camera motion analysis system (Vicon Motion Systems Ltd. London, UK). Three-dimensional ground
reaction force data were collected simultaneously at 1000Hz with two floor embedded force plates (AMTI Watertown, MA, USA) positioned in series in a 10-m walkway. A two second static standing trial with 45 markers was collected to define segment parameters and to estimate joint center locations. Single markers were then removed for movement testing except those on the pelvis, trunk and lower extremity marker clusters leaving 29 markers. All participants were asked to walk at their self-selected speed along a 10-m walkway. Five successful trials were collected for the test leg of all participants. A successful trial was defined as when the participants test foot made complete contact with one of the force plates.

**Gait Data Processing**

Visual 3D software (C-Motion, Inc, Rockville, MD) was used to process raw position and ground reaction force data. A 4th order Butterworth filter, with a cutoff frequency of 6Hz, was used to filter raw position and ground reaction force data. An 8-link segment kinematic model was built in Visual 3D using the CODA pelvis (Charnwood Dynamics Ltd. Leicestershire, UK). Joint coordinate systems were created, and segment position and orientation were determined using an unweighted least squares approach (Spoor & Veldpaus, 1980). A Cardan rotation sequence of X-Y’-Z’’ was applied to the joint coordinate systems such that this sequence represented the medial-lateral, anterior-posterior, and superior-inferior directions. All joint angles during movement trials were normalized to the static standing trial. Initial contact during the gait trials was defined by when the vertical ground reaction force (vGRF) exceeded 15 N and toe off was defined as when this vertical force was less than 15 N after initial contact. The next heel strike was defined using a marker based coordinate algorithm to identify the global minimum vertical position of the heel marker after the previous toe off was identified from the vGRF (Zeni et al., 2008).
Gait Data Analysis

The center of mass (CoM) of the model was calculated based on a weighted average of all the masses of the kinetic segments included in the model (i.e. segments used in inverse dynamic calculations). The CoM was a virtual point located within the center of the pelvis segment based on the segments contained in the model. Gait speed was defined as the average center of mass (CoM) velocity (m·s⁻¹) during a full stride of gait. CoM velocity was calculated as the first derivative of CoM position during a full non-time normalized stride of gait. A 5-trial ensemble average was calculated for each participant to represent each participant’s gait speed.

Peak hip joint angles were extracted from 5 full strides of gait and hip joint total range of motion (Tot. ROM) was calculated as the difference between the global maximum angle and global minimum angle during the stride. Five trial ensemble averages for each kinematic variable were calculated for analysis for each subject. All kinematic waveforms were then time normalized to 100 data points to represent percent of the gait cycle.

An inverse dynamics approach was used to calculate all net internal joint moments during gait. Peak hip joint moments (N-m) during the stance phase of 5 trials of gait were calculated for each plane of motion from the kinetic waveforms. Average frontal and sagittal plane joint moments were also calculated for stance phase, and the sagittal moments were separated into extension and flexion joint moments, respectively. All hip kinetics were normalized to body mass (N·m·kg⁻¹). Hip joint moment impulse for the sagittal and frontal planes were calculated as the product of the average internal joint moment and change in time of the joint moment during stance phase (N·m·s·kg⁻¹). For data analysis, five trial ensemble averages were calculated for all peak moments in all planes and for joint moment impulses, average joint moments, and impulse time for the sagittal and frontal planes. Positive values represent hip flexion, adduction, and internal rotation and negative values represent hip extension, abduction, and external rotation. All kinetic time series data were normalized to 100 data points to represent percent of stance phase.
Hip Passive of Range of Motion Measurement

All passive range of motion measurements were performed by a single examiner (P.M.). All PROM was measured using a standard long arm goniometer (Sammons and Preston Corp). Hip flexion, abduction, and external and internal rotation with the hip at 90 degrees of flexion were performed in the supine position according to standard physical examination techniques (Dutton, 2016). Hip internal and external rotation with the hip in 0 degrees of flexion was measured in the prone position.

Hip Muscle Strength Testing

Muscle strength is defined as a maximal external torque calculated as the product of the measured isometric external force (N) and the femoral length (m). Isometric external force (N) was measured using a hand-held dynamometer (Lafayette Instruments; Lafayette, Indiana) by a single examiner (PM). Femoral length (m) was measured as the distance between the greater trochanter and the lateral femoral epicondyle, Maximal external torque (N·m) was calculated as the product of the measured external force (N) and femoral length (m). All hip muscle strength was normalized to the participants body mass (N·m·kg⁻¹). All muscle testing involved the participants gradually increasing force, and generating maximal force for 3 seconds. Three maximal isometric contractions were collected on each leg and the average of the three trials for each leg was calculated and used for analysis. A 20 second rest period was given between each contraction to prevent fatigue. To measure the reliability of hip muscle strength a test-retest pilot study was conducted on 5 individuals with the average time between testing sessions being 10 ± 5.2 days. Cronbach’s alpha statistic was used to assess test-retest reliability. The Cronbach’s alpha values were .974, and .960 for hip flexion and hip abduction muscle strength testing, respectively. The results indicate excellent test-retest reliability for the hip muscle strength tests in the current study.
Hip flexion muscle strength was measured in a seated position with the hip at 80 degrees of flexion, which was confirmed by goniometric measurement. The participants placed each hand flat on the table beside their hip’s and were instructed to not hold the side of the table during testing. The pad of the hand-held dynamometer was placed on the anterior aspect of the distal thigh with the bottom edge of the pad in line with the lateral epicondyle of the femur (Figure 1). Participants were instructed to attempt to lift the thigh towards the ceiling pressing upward into the dynamometer.

Hip abduction muscle strength was measured with the participant in the side-lying position. The test hip (i.e. top leg) was placed in neutral rotation in all planes, which was confirmed by goniometric measurement. The bottom leg was placed in a position of mid-range hip and knee flexion to provide stability during testing. The hand-held dynamometer was placed in a custom foam pad to prevent slipping and discomfort on the lateral thigh during testing. The pad was aligned so that the inferior edge was in line with the knee joint and the center of the dynamometer pad was in line with the lateral epicondyle of the femur. The dynamometer was placed facing upward and was secured with a canvas strap that was attached to the treatment table (Figure 12). The examiner placed a stabilizing hand on the iliac crest of the test leg to prevent pelvic movement during the test. The participant was instructed to raise the test leg toward the ceiling pressing into the foam pad.
Figure 11. Isometric hip flexion strength testing

Figure 12. Isometric hip abduction strength testing

Statistical Analysis

All data were examined prior to analysis to determine if parametric statistical assumptions were met. In cases of parametric assumption violation, the appropriate non-parametric analog test was used for the analysis. The quantitative hip function variables of interest were: peak hip joint kinematics and kinetics in all planes, average sagittal and frontal plane moments, sagittal and frontal plane joint moment impulse, joint moment impulse time
during stance, hip PROM, and hip muscle strength. Paired samples \( t \)-tests were used to determine within group differences for the preoperative FAIS and postoperative groups. Independent samples \( t \)-tests were used to determine between group differences for control and preoperative FAIS and postoperative groups, respectively. A post-hoc bivariate Pearson’s product moment correlation analysis was performed to further examine linear associations between changes in biomechanical variables of hip function. The amount of change in these biomechanical variables was calculated as the difference between the postoperative and preoperative time points. An \textit{a-priori} alpha level of .05 was set for statistical significance. All statistical testing was performed using SPSS version 22 (IBM, Chicago, IL).

**Results**

A significant improvement in patient reported outcome scores was found after arthroscopic hip surgery for the Hip Outcome Score Activity of Daily Living Subscale (HOS-ADL) and the Nonarthritic Hip Score (NAHS) (Table 8).

A significant increase in hip passive range of motion and hip flexion muscle strength were also found after arthroscopic hip surgery (Table 9). The preoperative FAIS group demonstrated significantly less hip passive range of motion and hip flexion strength compared to the control group, however no differences were found between the postoperative and control groups for any clinical measure (Table 9).
Table 8. Participant demographics for preoperative FAIS (Pre.), postoperative (Post.) and matched controls (Control)

<table>
<thead>
<tr>
<th></th>
<th>Pre. (n=8)</th>
<th>Post. (n=8)</th>
<th>Control (n=8)</th>
<th>P-value (Pre. vs. Post.)</th>
<th>P-value (Pre. vs. Control)</th>
<th>P-value (Post. vs. Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>2F, 6M</td>
<td>2F, 6M</td>
<td>2F, 6M</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Age (Y)</td>
<td>22.3 (6.9)</td>
<td>23.4 (6.8)</td>
<td>22.3 (3.5)</td>
<td>.0001‡</td>
<td>.964</td>
<td>.682</td>
</tr>
<tr>
<td>Height (m.)</td>
<td>1.76 (.08)</td>
<td>1.78 (.10)</td>
<td>1.77 (.10)</td>
<td>.123</td>
<td>.694</td>
<td>.945</td>
</tr>
<tr>
<td>Body Mass (kg.)</td>
<td>76.0 (10.8)</td>
<td>78.4 (12.1)</td>
<td>74.3 (12.1)</td>
<td>.091</td>
<td>.769</td>
<td>.510</td>
</tr>
<tr>
<td>PRO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HOS-ADL (%)</td>
<td>68 (10)</td>
<td>91 (08)</td>
<td>--</td>
<td>.002†</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>NAHS</td>
<td>58.7 (14.7)</td>
<td>92.3 (8.2)</td>
<td>--</td>
<td>.0001‡</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Abbreviations: Y = years; m. = meters; kg. = kilograms; PROs = Patient reported outcomes; HOS-ADL = Hip Outcome Score Activity of Daily Living Subscale; NAHS = Nonarthritic Hip Score. * indicates statistical significance at p < .05; † indicates statistical significance at p < .005; ‡ indicates statistical significance at p < .0005

Significant differences in hip biomechanics during gait were found after arthroscopic hip surgery for FAIS. During the stance phase of gait, increases in peak hip flexion moments and hip flexion joint impulse were found (Tables 10 & 11) (Figure 13). Conversely, decreases in the average hip extension moment and hip extension joint impulse were found after arthroscopic hip surgery for FAIS (Table 11) (Figure 13).

Between-group differences revealed lower peak hip adduction moments in the control group when compared to the preoperative FAIS group (Table 10) (Figure 14). Similarly, a significant difference in hip flexion joint impulse was also found between postoperative and control group (Table 11). No other between- or within-group differences were found for any other kinetic variable (Table 10 & 11). No between- or within-group differences in hip joint kinematic variables of function were found (Table 12, Figure 15A-C).
Table 9. Mean (SD) for hip passive range of motion (°) and muscle strength (N·m·kg\(^{-1}\)) for the preoperative FAIS (Pre.), postoperative (Post.), and control groups.

<table>
<thead>
<tr>
<th>PROM</th>
<th>Pre.</th>
<th>Post.</th>
<th>Control</th>
<th>P-value (Pre. vs. Post.)</th>
<th>P-value (Pre. vs. Control)</th>
<th>P-value (Post. vs. Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>100</td>
<td>109.8</td>
<td>110.6</td>
<td>.0004‡</td>
<td>.0001‡</td>
<td>.736</td>
</tr>
<tr>
<td></td>
<td>(3.8)</td>
<td>(5.6)</td>
<td>(4.3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abduction</td>
<td>29.1</td>
<td>31.6</td>
<td>36.8</td>
<td>.229</td>
<td>.019*</td>
<td>.089</td>
</tr>
<tr>
<td></td>
<td>(8.0)</td>
<td>(7.6)</td>
<td>(2.7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR 90°</td>
<td>9.4</td>
<td>28.3</td>
<td>28.9</td>
<td>.0001‡</td>
<td>.0001‡</td>
<td>.805</td>
</tr>
<tr>
<td></td>
<td>(4.2)</td>
<td>(5.9)</td>
<td>(2.9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER 90°</td>
<td>41.2</td>
<td>48.5</td>
<td>46.4</td>
<td>.0001‡</td>
<td>.324</td>
<td>.642</td>
</tr>
<tr>
<td></td>
<td>(12.5)</td>
<td>(10.6)</td>
<td>(7.8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR at 0°</td>
<td>24.4</td>
<td>32.1</td>
<td>37.4</td>
<td>.0005†</td>
<td>.003†</td>
<td>.271</td>
</tr>
<tr>
<td></td>
<td>(10.0)</td>
<td>(12.8)</td>
<td>(2.7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ER at 0°</td>
<td>36.0</td>
<td>40.1</td>
<td>39.6</td>
<td>.054</td>
<td>.371</td>
<td>.904</td>
</tr>
<tr>
<td></td>
<td>(9.6)</td>
<td>(9.5)</td>
<td>(6.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>1.06</td>
<td>1.70</td>
<td>1.66</td>
<td>.024*</td>
<td>.0009‡</td>
<td>.859</td>
</tr>
<tr>
<td></td>
<td>(.34)</td>
<td>(.52)</td>
<td>(.28)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abduction</td>
<td>1.55</td>
<td>1.67</td>
<td>1.84</td>
<td>.491</td>
<td>.128</td>
<td>.342</td>
</tr>
<tr>
<td></td>
<td>(.43)</td>
<td>(.40)</td>
<td>(.27)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: PROM = passive range of motion; IR 90° = internal rotation at 90 degrees of hip flexion; ER 90° = external rotation at 90 degrees of hip flexion; IR 0° = internal rotation at 0 degrees of hip flexion; ER 0° = external rotation at 0 degrees of hip flexion

* indicates statistical significance at p < .05; † indicates statistical significance at p < .005
‡ indicates statistical significance at p < .0005
Table 10. Mean (SD) for peak hip joint moments in each plane (N·m·kg⁻¹) during gait for the preoperative FAIS (Pre.), postoperative (Post.), and control groups.

<table>
<thead>
<tr>
<th></th>
<th>Pre.</th>
<th>Post.</th>
<th>Control</th>
<th>P-value (Pre. vs. Post.)</th>
<th>P-value (Pre. vs. Control)</th>
<th>P-value (Post. vs. Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pk. Ext.</td>
<td>-.62</td>
<td>-.58</td>
<td>-.60</td>
<td>.066</td>
<td>.596</td>
<td>.665</td>
</tr>
<tr>
<td></td>
<td>(.12)</td>
<td>(.12)</td>
<td>(.05)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pk. Flex.</td>
<td>.96</td>
<td>1.07</td>
<td>.96</td>
<td>.036*</td>
<td>.979</td>
<td>.203</td>
</tr>
<tr>
<td></td>
<td>(.14)</td>
<td>(.15)</td>
<td>(.20)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pk. Add.</td>
<td>.11</td>
<td>.10</td>
<td>.06</td>
<td>.508</td>
<td>.046*</td>
<td>.195</td>
</tr>
<tr>
<td></td>
<td>(.04)</td>
<td>(.06)</td>
<td>(.06)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pk. Abd</td>
<td>-1.00</td>
<td>-.93</td>
<td>-.88</td>
<td>.335</td>
<td>.264</td>
<td>.436</td>
</tr>
<tr>
<td></td>
<td>(.26)</td>
<td>(.11)</td>
<td>(.15)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pk. IR</td>
<td>.04</td>
<td>.07</td>
<td>.04</td>
<td>.154</td>
<td>.990</td>
<td>.258</td>
</tr>
<tr>
<td></td>
<td>(.03)</td>
<td>(.04)</td>
<td>(.03)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pk. ER</td>
<td>-.29</td>
<td>-.28</td>
<td>-.25</td>
<td>.303</td>
<td>.518</td>
<td>.907</td>
</tr>
<tr>
<td></td>
<td>(.17)</td>
<td>(.13)</td>
<td>(.09)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: Pk. Flex = peak flexion; Pk. Ext. = peak extension; Pk. Add. = peak adduction; Pk. Abd. = peak abduction; Pk. IR = peak internal rotation; Pk. ER = peak external rotation.

* indicates statistical significance at p < .05
Figure 13. Sagittal plane hip joint moment waveforms during the stance phase of gait for the preoperative FAIS (dark grey dot), postoperative (grey solid), and control (black solid).

Table 11. Mean (SD) sagittal and frontal hip joint moment impulse (N·m·s·kg⁻¹), joint moment impulse time (seconds) and average joint moments (N·m·kg⁻¹) during the stance phase of gait for the preoperative FAIS (Pre.), postoperative (Post.) and control groups.

<table>
<thead>
<tr>
<th></th>
<th>Pre.</th>
<th>Post.</th>
<th>Control</th>
<th>P-value (Pre. vs. Post.)</th>
<th>P-value (Pre. vs. Control)</th>
<th>P-value (Post. vs. Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ext. Imp.</td>
<td>-.08</td>
<td>-.06</td>
<td>-.07</td>
<td>.019*</td>
<td>.617</td>
<td>.504</td>
</tr>
<tr>
<td>Ext. Imp. Time</td>
<td>.18</td>
<td>.17</td>
<td>.19</td>
<td>.760</td>
<td>.555</td>
<td>.732</td>
</tr>
<tr>
<td>Avg. Ext. Mom.</td>
<td>-.39</td>
<td>-.36</td>
<td>-.35</td>
<td>.004†</td>
<td>.330</td>
<td>.875</td>
</tr>
<tr>
<td>Flex. Imp.</td>
<td>.23</td>
<td>.27</td>
<td>.22</td>
<td>.012*</td>
<td>.977</td>
<td>.025*</td>
</tr>
<tr>
<td>Flex. Imp. Time</td>
<td>.48</td>
<td>.51</td>
<td>.48</td>
<td>.073</td>
<td>.825</td>
<td>.203</td>
</tr>
<tr>
<td>Avg. Flex. Mom.</td>
<td>.47</td>
<td>.56</td>
<td>.46</td>
<td>.052</td>
<td>.859</td>
<td>.075</td>
</tr>
<tr>
<td>Abd. Imp.</td>
<td>-.37</td>
<td>-.33</td>
<td>-.36</td>
<td>.170</td>
<td>.678</td>
<td>.451</td>
</tr>
<tr>
<td>Abd. Imp. Time</td>
<td>.60</td>
<td>.61</td>
<td>.62</td>
<td>.716</td>
<td>.460</td>
<td>.379</td>
</tr>
<tr>
<td>Avg. Abd. Mom.</td>
<td>.61</td>
<td>.58</td>
<td>.57</td>
<td>.471</td>
<td>.425</td>
<td>.568</td>
</tr>
</tbody>
</table>

Abbreviations: Ext. Imp. = extension moment impulse; Flex. Imp = flexion moment impulse; Ext. Imp. Time = extension joint moment impulse time; Flex. Imp. Time = flexion joint moment impulse time; Avg. Ext. Mom. = average extension moment; Avg. Flex. Mom = average flexion moment; Abd. Imp. = abduction joint moment impulse; Abd. Imp. Time = abduction impulse time; Avg. Abd. Mom. = average abduction moment.

* indicates statistical significance at p < .05
† indicates statistical significance at p < .005
Figure 14. Frontal plane hip joint moment waveforms during the stance phase of gait for the preoperative (dark grey dot), postoperative (grey solid), and control (black solid) groups.

Table 12. Mean (SD) hip joint angles and total range of motion in degrees (°) during gait for the preoperative FAIS (Pre.), postoperative (Post.) and control groups.

<table>
<thead>
<tr>
<th>Sagittal</th>
<th>Pre.</th>
<th>Post.</th>
<th>Control</th>
<th>P-value (Pre. vs. Post.)</th>
<th>P-value (Pre. vs. Control)</th>
<th>P-value (Post. vs. Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pk. Flex.</td>
<td>35.6</td>
<td>33.8</td>
<td>32.5</td>
<td>.477</td>
<td>.380</td>
<td>.979</td>
</tr>
<tr>
<td></td>
<td>(5.8)</td>
<td>(6.6)</td>
<td>(7.8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pk. Ext.</td>
<td>-4.0</td>
<td>-5.8</td>
<td>-7.0</td>
<td>.484</td>
<td>.377</td>
<td>.922</td>
</tr>
<tr>
<td></td>
<td>(7.9)</td>
<td>(8.9)</td>
<td>(5.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tot. ROM</td>
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<td>39.5</td>
<td>.936</td>
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<td>.894</td>
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<tr>
<td></td>
<td>(3.8)</td>
<td>(3.5)</td>
<td>(5.3)</td>
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<td></td>
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<tr>
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<td>.570</td>
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<td>(3.9)</td>
<td>(3.8)</td>
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<tr>
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<td>-5.2</td>
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<td>.345</td>
<td>.332</td>
</tr>
<tr>
<td></td>
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<td>(3.7)</td>
<td>(3.7)</td>
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<tr>
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<td>9.9</td>
<td>.382</td>
<td>.725</td>
<td>.243</td>
</tr>
<tr>
<td></td>
<td>(2.1)</td>
<td>(2.1)</td>
<td>(6.4)</td>
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<td></td>
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<tr>
<td>Transverse</td>
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<td></td>
<td></td>
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<tr>
<td>Pk. IR</td>
<td>2.7</td>
<td>3.3</td>
<td>2.9</td>
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<td>.842</td>
<td>.456</td>
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<tr>
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<td>(5.5)</td>
<td>(3.5)</td>
<td>(4.5)</td>
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<tr>
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<td>(4.2)</td>
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<tr>
<td>Tot. ROM</td>
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<td>9.8</td>
<td>.358</td>
<td>.688</td>
<td>.596</td>
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<td>(3.1)</td>
<td>(2.7)</td>
<td>(6.0)</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Abbreviations: Pk. Flex = peak flexion; Pk. Ext. = peak extension; Pk. Add. = peak adduction; Pk. Abd. = peak abduction; Pk. IR = peak internal rotation, Pk. ER = peak external rotation; Tot. ROM = Total range of motion.
Figure 15. Hip joint kinematic waveforms during walking in the sagittal (A), frontal (B), and transverse (C) planes of motion for preoperative FAIS patients (dark grey dot), postoperative hip arthroscopy patients (grey solid), and healthy matched controls (black solid). All joint angle waveforms are reported in degrees (°).

**Discussion**

The purpose of this study was to determine the effect of arthroscopic hip surgery for FAIS on clinical and biomechanical measures of hip joint function. The results of this study demonstrate partial support for the hypothesis that quantitative hip joint function improves after arthroscopic hip surgery. A significant increase in hip passive range of motion and hip flexion strength indicates clinical improvement in hip joint function after arthroscopic surgery. In addition, greater post-operative peak hip flexion moments and hip flexion moment impulse during gait were observed, whereas hip extension moment impulse and average hip extension moments decreased. Contrary to our hypotheses and previous studies, no differences in peak hip joint kinematics during gait were observed after arthroscopic hip surgery (J. Rylander et al., 2013; J. H. Rylander et al., 2011). The findings from the current study are the first to demonstrate
alterations in hip kinetics during gait after arthroscopic hip surgery for FAIS. Together the results of the current study indicate a quantitative clinical improvement in hip function after arthroscopic hip surgery. However, further research is needed to determine if the kinetic alterations observed are positive or negative indications of the preservation of long-term hip joint function.

The current findings are novel and provide quantitative evidence of improved clinical hip joint function after surgery. Hip flexion, internal and external rotation passive range of motion and hip flexion muscle strength increased after arthroscopic hip surgery for FAIS. Recently it has been shown that impairments in hip strength and range of motion are common clinical signs of FAIS and serve as good measures of disease impact (Griffin et al., 2016; Reiman et al., 2017). The passive range of motion findings in the current study are not surprising because arthroscopic hip surgery for FAIS involves removal of excess bone that is responsible for symptomatic impingement during hip motion. However, the observed increases in hip flexion muscle strength in the current study are not consistent with previous findings (N. C. Casartelli et al., 2014). Casartelli and colleagues showed no improvements in hip flexion muscle strength in athletes who were greater than 2.5 year post arthroscopic hip surgery for FAIS (N. C. Casartelli et al., 2014). Perhaps one reason for the difference in findings is that the current study used a handheld dynamometer to measure strength whereas the previous study used an isokinetic dynamometer to quantify hip flexion and extension muscle strength. Interestingly, the previous authors measured the frontal and transverse plane hip muscles using a handheld dynamometer and did find significant increases in hip strength for these muscle groups using this method. Therefore, the inconsistent findings between the current and previous study may simply reflect differences in the specific techniques with which strength was measured (N. C. Casartelli et al., 2014). Moreover, the previous study sample was predominantly athletes whereas the current sample was taken from the general population. Despite the inconsistencies in post-operative changes in hip flexion muscle strength between the current and previous studies, the results of the current study do
support that clinical measures of hip function are improved after arthroscopic hip surgery for FAIS.

Another novel finding from the current study was the significant alteration in sagittal plane hip kinetics during gait after arthroscopic hip surgery. A significant increase in the peak hip flexion joint moment and hip flexion moment impulse were observed, whereas a decrease in hip extension impulse and average hip extension moment occurred during the stance phase of gait. The postoperative increase in hip flexion impulse during gait can be explained by the increase in the peak hip flexion moment, while the decrease in hip extension impulse was driven by a large reduction in the average hip joint extension moment. It is interesting that the postoperative sagittal plane joint impulse increased in the flexion direction, but decreased in the extension direction during the stance phase of gait. Considering that the hip flexion impulse has been reported to be a potentially important biomechanical parameter in people with FAIS it seems relevant to further explore this potential relationship (Samaan et al., 2016). An explanation may be that after arthroscopic hip surgery people adopt a kinetic strategy that redistributes the sagittal plane joint moments during the stance phase of gait to accommodate a tolerance to greater forces in the anterior direction, while balancing the overall joint load. Arguably, a greater peak hip flexion moment could result in a larger anteriorly directed hip joint force during gait, especially since this peak moment occurs with the hip in an extended position during the terminal stance phase (Correa et al., 2010; Lewis et al., 2007). Perhaps a reduction in anterior hip symptoms after arthroscopic hip surgery allows for the tolerance of greater anterior joint forces during gait. In turn, the reduction in the average hip extension moments may reflect a reduced effort from the hip extensors, which also contribute considerably to joint force. The combination of these stance phase compensations may therefore represent an attempt to balance the magnitude of the overall joint forces during the stance phase of gait (Correa et al., 2010; Lewis et al., 2007). We explored this relationship with a post hoc correlation analysis to determine the association between the postoperative change in peak hip flexion moments and postoperative change in average hip
extension moments. This analysis revealed that the change in average hip extension moment explained approximately 50% of the variance in the change in the peak hip flexion moment ($r = .709, p = .022$), which indicates a strong association ($r > .70$) between the postoperative change in these sagittal plane kinetic variables during the stance phase of gait.

It is still not clear, however, whether the changes in sagittal plane kinetics represent an improvement in actual biomechanical hip joint function. Peak hip adduction moments were the only kinetic variable that differed between the preoperative FAIS group and healthy controls. The postoperative group also demonstrated significantly greater hip flexion joint moment impulse than the healthy control group. The difference in hip flexion moment impulse between these groups seems to be driven by the statistical trend towards a greater average hip flexion moment ($p = .077$). Although after arthroscopic hip surgery one may predict that postoperative individuals would resemble healthy controls, other studies have also found alterations in gait and functional performance exists at greater than a year after arthroscopic hip surgery (J. L. Kemp et al., 2016). Perhaps similar to other orthopedic surgical procedures, such as an anterior cruciate ligament reconstruction, an extended dynamic gait adjustment period occurs over a long period of time to optimize joint function (Capin, Zarzycki, Arundale, Cummer, & Snyder-Mackler, 2017; Paterno, Ford, Myer, Heyl, & Hewett, 2007). Also, since arthroscopic hip surgery for FAIS involves structural modification to increase hip joint motion, a similar neuromuscular adaption period may occur. Further research is needed to determine the long-term impact of the observed biomechanical alteration in hip function after arthroscopic hip surgery. Clinically, it is important to acknowledge that alterations in hip biomechanical function exists greater than one year after surgery. Rehabilitation programs should be tailored to an individual’s functional demands and with respect to the length of time it may take for hip biomechanical joint function to be normalized, despite significant improvement in clinical measures of hip joint function and patient reported outcomes.
Although the current study provides novel information on kinetic alterations during gait after arthroscopic hip surgery, this investigation is not without limitation. While the sample size of the current study may be considered small, previous investigations on the effects of surgery for FAI had an average of 12 participants, so the current samples size of 8 participants (10 postoperative hips) is comparable (Brisson et al., 2013; Lamontagne et al., 2011; J. Rylander et al., 2013; J. H. Rylander et al., 2011). The authors further acknowledge that imaging was not used to confirm the presence of cam or pincer type morphology in the control group. However, since FAIS is not isolated to only imaging findings we feel that the current method of screening was sufficient to screen for FAIS, and consistent with methods of a previous study (Hunt et al., 2013). Additionally, although joint moment impulse may serve as a proxy for joint loading, the current study did not quantify joint contact forces during gait. Therefore, it is outside of the current results to determine if the observed changes in joint kinetics represent an improvement or decrement in biomechanical joint function after surgery.
Introduction

Femoroacetabular impingement syndrome (FAIS) is a clinical hip disorder that encompasses hip related symptoms, clinical signs, and imaging findings (Griffin et al., 2016). This disorder is characterized by a structural anomaly of the proximal femur or acetabulum that are referred to as cam or pincer morphology, respectively. During dynamic activity, these morphologies can result in painful premature contact between the femur and acetabulum (Griffin et al., 2016). The common clinical signs of FAIS include a loss of hip flexion and internal rotation range of motion and the reproduction of pain or symptoms during these combined motions (Griffin et al., 2016). Perhaps what is most significant about FAIS is that it has been linked to hip joint injury, such as acetabular labral tears and osteoarthritis (OA) (Bedi & Kelly, 2013; Clohisy et al., 2013; Ganz et al., 2003). Consequently, arthroscopic hip surgery for FAIS has grown at an exponential rate in recent years and demonstrates very good to excellent short to midterm outcomes for hip pain relief and improved patient reported function (Bozic et al., 2013; Levy et al., 2016; Menge et al., 2017). Although this evidence is encouraging, limited evidence exists on how arthroscopic hip surgery for FAIS impacts joint dynamics during functional activities (Brisson et al., 2013; Lamontagne et al., 2011; J. Rylander et al., 2013; J. H. Rylander et al., 2011). Perhaps more importantly, there is a lack of evidence on how the dynamic problem of FAIS may alter motor control of the hip joint during a functional activity such as gait. An improved understanding of hip joint control in persons with FAIS both before and after arthroscopic hip surgery will assist in the development of targeted rehabilitation programs designed to address these potential hip joint motor control deficits.
The evidence on whether hip joint kinematic control is altered during gait before and after arthroscopic hip surgery for FAIS remains unclear (Brisson et al., 2013; L. E. Diamond et al., 2016; Kennedy et al., 2009; J. Rylander et al., 2013; J. H. Rylander et al., 2011). Most studies have been limited to the measurement of discrete kinematic variables, which provide little information on the central control strategy during gait (Brisson et al., 2013; L. E. Diamond et al., 2016; Hunt et al., 2013; Kennedy et al., 2009; J. Rylander et al., 2013; J. H. Rylander et al., 2011). Recently it has been shown that persons with FAIS and acetabular cartilage injury do have alterations in hip muscle and lower extremity joint coordination during walking (L. E. Diamond et al., 2017; Samaan et al., 2015). These findings suggest that central motor control may be altered in persons with FAIS, however, it remains unknown as to how these central control alterations may manifest as kinematic changes at the hip during function. Perhaps of more concern is that despite arthroscopic hip surgery being intended to eliminate premature symptomatic contact of the hip joint during dynamic motion, no study has investigated if dynamic hip joint control is improved after surgery for FAIS.

To simplify motor control of joint kinematics during a task such as gait, the central nervous system reduces the redundant degrees of freedom within the musculoskeletal system (Courtine, Papaxanthis, & Schieppati, 2006; Courtine & Schieppati, 2004; Ivanenko, Cappellini, Dominici, Poppele, & Lacquaniti, 2007; Ivanenko, d'Avella, Poppele, & Lacquaniti, 2008). One way in which the central nervous system reduces these degrees of freedom is through the constraint of the covariation between the joint angular kinematic degrees of freedom (i.e. planes of motion) during a task such as gait (Borghese, Bianchi, & Lacquaniti, 1996; Ivanenko et al., 2007; Ivanenko et al., 2008). The investigation of the covariation between joint angular degrees of freedom provides insight into the three-dimensional (3D) kinematic control strategy of the joint during a task (Ivanenko et al., 2008). Previous research has shown that persons with FAIS demonstrate alterations in the central control of muscle activation synergies, lower limb segment coordination, and differences in discrete gait kinematics (L. E. Diamond et al., 2017; Hunt et al.,
2013; Kennedy et al., 2009; J. Rylander et al., 2013; J. H. Rylander et al., 2011; Samaan et al., 2015). However, very little evidence exists on the impact of arthroscopic hip surgery for FAIS on hip joint dynamics (J. Rylander et al., 2013; J. H. Rylander et al., 2011). Therefore, it is important to investigate the effect of arthroscopic hip surgery for FAIS on the central control strategy during gait. This information could assist in developing targeted neuromuscular rehabilitation programs aimed at dynamic kinematic control of the hip during functional tasks, such as gait.

Principal components analysis (PCA) is a multivariate statistical technique that is used to extract orthogonal modes of variation within a data set (Ramsay, 2006). PCA has been applied to biomechanical waveform data to analyze movement patterns across a variety of pathologic conditions and functional tasks (Astephen, Deluzio, Caldwell, Dunbar, & Hubley-Kozey, 2008; Astephen et al., 2008; Daffertshofer, Lamoth, Meijer, & Beek, 2004; K. J. Deluzio et al., 1997; K. Deluzio & Astephen, 2007; Kipp et al., 2011; O'Connor & Bottum, 2009; Wrigley, Albert, Deluzio, & Stevenson, 2006). PCA has also been applied to the covariance matrix of three-dimensional joint kinematic time series to determine the angular co-variation of joint degrees of freedom during functional tasks (Borghese et al., 1996; Ivanenko et al., 2007; Kipp & Palmieri-Smith, 2013). In this type of analysis, the first two principal components define the axes of a plane that represents the three-dimensional coordination between the joint angle degrees of freedom (i.e. planes of hip joint motion) (Borghese et al., 1996; Kipp & Palmieri-Smith, 2013). A linear kinematic control strategy would be shown by a large proportion of the variance being explained by the first principal component (PC1), whereas a more planar kinematic control strategy would be demonstrated by a larger proportion of the variance being shared by the second principal component (PC2) (Borghese et al., 1996; Kipp & Palmieri-Smith, 2013). In general, the shared variance between two principal components indicates how well the joint angular degrees of freedom are coordinated during movement and therefore reflects the complexity of the motor control strategy. For example, tight coordination (i.e. linear kinematic control strategy) of the
joint angular degrees of freedom during a task translates to a simpler motor control strategy, whereas a more complex motor control strategy is represented by less coordination (i.e. planar kinematic control strategy) between the joint angular degrees of freedom during the task (Ivanenko et al., 2007; Ivanenko et al., 2008).

The investigation of the hip kinematic control strategy during gait through a joint angle co-variation paradigm can provide novel insight into the potential alterations in the central control mechanism in persons with FAIS before and after arthroscopic hip surgery. Ultimately, this information will be used to develop targeted rehabilitation programs for persons with FAIS through a better understanding of central control alterations in these patients. The aim of the current study is to determine if the kinematic control strategy of the hip joint during gait is altered before and after arthroscopic hip surgery for FAIS. It is hypothesized that persons with FAIS will demonstrate a more complex kinematic control strategy as compared to healthy controls and that this strategy will improve after arthroscopic hip surgery such that it resembles that of healthy controls.

**Methods**

**Participants**

All participants were recruited from a private orthopedic surgery practice by a single surgeon who specializes in the treatment of hip disorders. The diagnosis of FAIS included the presence of *all of the following criterion*: 1) hip pain > 3 months; 2) a positive anterior impingement (FADIR) test; 3) radiographic evidence of cam or pincer or mixed morphology as defined by *any of the following*: alpha angle >55° (cam type); center edge angle >40° (pincer type); or confirmed crossover sign (pincer type); 4) Tonnis grade ≤ 1 on standard radiograph; 5) magnetic resonance imaging with no evidence of diffuse articular cartilage degeneration; 6) positive response to an intra-articular anesthetic injection, which was defined as the temporary
pain relief during impingement testing immediately after the injection. Participants with FAIS were also excluded if they had: (1) low back pain or pain in any other lower extremity joint (2) history of hip fracture or dislocation, (4) previous diagnosis of any developmental hip conditions, and (5) any systemic disorders that limit the performance of activities of daily living and (6) history of lower extremity surgery of any kind.

All FAIS participants underwent arthroscopic hip surgery by a board certified orthopedic surgeon who specializes in arthroscopic hip surgery. The arthroscopic hip surgery consisted of some or all of the following based on the preoperative and postoperative diagnoses: femoral neck osteochondroplasty, acetabular rim trimming, labral debridement or refixation, ligamentum teres debridement, microfracture, and capsular closure. No patients underwent a labral reconstruction procedure.

Eight persons diagnosed with FAIS who underwent arthroscopic hip surgery were recruited for this study. Two persons underwent bilateral arthroscopic surgery 6 months apart, so 10 hips in total were included for analysis. Eight gender, height, and body mass matched controls were included in the analysis with bilateral data being included for 2 control participants (i.e. 10 hips) (Table 13).

A convenience sample of healthy gender, body mass, and height matched controls from the general university population were also recruited. Since the diagnosis of FAIS is not isolated to imaging findings that indicate cam or pincer morphology, the control participants in the current study were screened for these potential morphologies using a screening examination like what has been previously reported (Hunt et al., 2013). The screening examination was performed by a single licensed physical therapist (PM) with > 13 years’ experience treating FAIS. The screening examination consisted of a VAS pain questionnaire, hip passive range of motion measurements, and a hip physical examination. The hip physical examination consisted of a cluster of hip special tests to rule out intra-articular pathology (Griffin et al., 2016; Martin et al., 2008; Martin & Sekiya, 2008; Martin et al., 2010). These tests included: the anterior impingement test (FADIR
test), FABER test, log roll test, and the dial test (Byrd, 2007; Ganz et al., 2003; Griffin et al., 2016; Martin et al., 2008; Martin et al., 2010; Philippon et al., 2007). Although these tests lack specificity, they have been shown to demonstrate good sensitivity in ruling out intra-articular pathology (Martin et al., 2008; Martin & Sekiya, 2008). Control participants were excluded if they demonstrated any of the following during the screening examination: (1) pain in any lower extremity joint or low back, (2) history of lower extremity or low back injury within the last 6 months, (3) any history of lower extremity fracture or surgery, (4) hip flexion less than 85° and internal rotation less than 10° at 90° of hip flexion, (5) hip pain or symptoms reported with any physical examination test for hip pathology. This study was approved by the local universities office of research compliance. All participants provided a written informed consent before participation in the study.

Table 13. Participant demographics for preoperative FAIS (Pre.), postoperative (Post.) and matched controls (Control).

<table>
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<tr>
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<th>Pre. (n=8)</th>
<th>Post. (n=8)</th>
<th>Control (n=8)</th>
<th>P-value (Pre. vs. Control)</th>
<th>P-value (Pre. vs. Post)</th>
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<td>22.3 (3.5)</td>
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PROs

<table>
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<td>.91 (.08)</td>
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<tr>
<td>NAHS</td>
<td>58.7 (14.7)</td>
<td>92.3 (8.2)</td>
<td>--</td>
<td>.002†</td>
</tr>
</tbody>
</table>

Abbreviations: PROs = patient reported outcomes of function; Y = years; m. = meters; kg. = kilograms; HOS-ADL = Hip Outcome Score Activity of Daily Living Subscale; NAHS = Nonarthritic Hip Score.

* indicates statistical significance at p < .05
† indicates statistical significance at p < .005
‡ indicates statistical significance at p < .0005
**Gait Analysis**

Eight people who underwent arthroscopic hip surgery for FAIS participated in preoperative and postoperative biomechanical gait testing. Postoperative biomechanical gait testing was completed at > 12 months after surgery (15.2 ± 3.9 months). The eight matched healthy controls completed a single biomechanical testing session. The biomechanical testing consisted of three-dimensional (3D) gait analysis as part of a larger study. The 3D gait analysis consisted of retro-reflective markers being placed on anatomical landmarks of the trunk, pelvis, and bilateral lower extremities. Position data from 29 markers on the trunk, pelvis, and lower extremities were collected at 100Hz with a 14-camera motion analysis system (Vicon Motion Systems Ltd. London, UK). Markers were attached to the sternal notch, C7, T10, bilateral PSIS and ASIS, and rigid marker clusters on the bilateral thighs (4), shanks (4) and feet (3). Prior to gait testing a static standing trial was collected with an additional 16 markers to define joint segments and estimate joint center locations (45 markers total).

Gait testing consisted of participants walking at a self-selected speed down a 10-meter walkway. A self-selected walking speed was chosen as this would mimic the individuals pattern and kinematic strategies outside of the research lab. Data were collected on the matched control’s dominant leg for comparison as defined by the leg with which they would kick a ball. Bilateral data were analyzed on 2 controls to match the bilateral FAIS participants. During the gait testing the participants walked across two force plates in series (AMTI, Watertown, MA, USA), which simultaneously collected force data at 1000Hz. The ground reaction force data were used to define the initial heel strike and toe off during the gait cycle (stance phase). Heel strike was defined as when the vertical ground reaction force (vGRF) exceeded 15 N and toe off was defined as when this vertical force was less than 15 N after initial contact. The next consecutive heel strike was used to define a full gait cycle (i.e. stride) and was identified using a heel marker
coordinate based algorithm. The algorithm identified the global minimum vertical position of the heel marker after the previous toe off was identified from the vGRF (Zeni et al., 2008). A successful trial was defined as when the participants test limb made complete contact with one of the force plates.

Raw position and ground reaction force data were processed in Visual 3D (C-Motion, Inc, Rockville, MD). A 4th order Butterworth filter with a cutoff frequency of 6Hz was used to filter raw position and ground reaction force data. An 8-link segment kinematic model was built in Visual 3D using the filtered position data and by using a CODA pelvis segment (Charnwood Dynamics Ltd. Leicestershire, UK). The hip joint position and orientation of the model was calculated using a joint coordinate systems approach (Spoor & Veldpaus, 1980). Hip joint rotations were calculated using a Cardan rotation sequence of the thigh segment relative to the pelvis segment such that the X-Y’-Z” sequence represented the medial-lateral, anterior-posterior, and superior-inferior directions. All hip joint angles during movement trials were normalized to the static standing trial. All raw 3D hip joint kinematic waveforms from each of the 5 successful gait trials were time normalized to 100 data points to represent percent gait cycle. 3D hip joint angle data (X, Y, Z) were extracted for 5 trials of a full gait cycle for each participant and used as input for into a principal components analysis.

The center of mass (CoM) of the model was calculated based on a weighted average of all the masses of the kinetic segments included in the model (i.e. segments used in inverse dynamic calculations). The CoM was a virtual point located within the center of the pelvis segment based on the segments contained in the model. Gait speed was defined as the average center of mass (CoM) velocity (m·s⁻¹) during a full stride of gait. CoM velocity was calculated as the first derivative of CoM position during a full non-time normalized stride of gait. A 5-trial ensemble average was calculated for each participant to represent each participant’s gait speed.
Planar Co-variation Analysis

To place emphasis on the temporal structure of the data and to prevent the differences in magnitudes of the hip joint angles in each plane (i.e. spatial structure) from driving the analysis, all 3D joint kinematic data were z-scored prior to analysis. This was done by subtracting the time series mean from each point and dividing by the time series standard deviation (St-Onge & Feldman, 2003). A principal component analysis (PCA) using an eigenvector decomposition algorithm was performed on the co-variance matrix of the z-scored 3D hip joint kinematic time series. This analysis extracted the eigenvalues and eigenvectors (i.e. principal components - PC) from the co-variance matrix of the z-scored 3D hip joint kinematic time series (Courtine & Schieppati, 2004; Kipp & Palmieri-Smith, 2013). The eigenvalues were used to calculate the variance proportion (%) accounted for by each of the principal components by dividing the eigenvalue for each PC by the sum of the all the eigenvalues. In the current study, all the variance proportion was accounted for by the first two PCs, which is consistent with previous investigations (Borghese et al., 1996). Since each joint angle could be reconstructed through the linear combination of all the PCs, the contribution of each PC to the joint angle time series was also estimated by calculating the PC scores for each contributing joint angle. The PC scores represent how much each joint angle contributed to shaping the plane of covariation (i.e. kinematic pattern). A 5-trial ensemble average for all the variance proportions accounted for by each PC (i.e. kinematic control strategy) and the PC scores for each angle (i.e. joint specific contribution) were calculated for each person in the preoperative FAIS group (Pre.), postoperative group (Post.), and control group. All data analysis were performed using a custom written MATLAB program.
Statistical Analysis

All data were screened prior to analysis to determine if parametric statistical assumptions were met. In cases of parametric assumption violation, the appropriate non-parametric analog test was used for the analysis. The dependent variables included in the analysis were the ensemble averaged PC variances and PC scores for each joint angle time series. An independent sample t-test was used to determine between group differences for and preoperative FAIS and control group. A paired samples t-test was used to determine within group differences for the preoperative FAIS and postoperative group. An a-priori alpha level of .05 was set for statistical significance. All statistical testing was performed using SPSS version 22 (IBM, Chicago, IL).

Results

There were no between-group differences in self-selected gait speed for the preoperative FAIS group and healthy controls (Pre., 1.36 (.10) vs. Control, 1.40 (.16) m/s; \(p = .592\)), or within-group differences before and after arthroscopic hip surgery (Pre., 1.36 (.10) vs. Postop 1.35 (.06) m/s; \(p = .704\)).

A significant difference was found in the percent variance accounted for by each of the principal components between the preoperative FAIS group and healthy controls. The variance accounted for by the first PC (PC1) for the preoperative FAIS group was significantly less than that of healthy controls (FAIS, 77.2 (8.7) % vs. Control, 96.1 (2.8) %; \(p = .0001\)). Additionally, the variance accounted for by the second PC (PC2) was significantly greater for the preoperative FAIS group when compared to healthy controls (22.8 (8.7) % vs. 3.9 (2.8) %; \(p = .0001\)). These results indicate that before surgery people with FAIS demonstrate a planar kinematic strategy when compared to healthy controls (Figure 16).

Conversely no within-group differences were found between the variance accounted for by PC 1 (77.2 (8.7) % vs. 79.3 (11.1) %; \(p = .472\)) or PC2 (22.7 (8.7) % vs. 20.7 (11.1) %; \(p =
.472), before and after hip arthroscopic surgery for FAIS. This finding indicates that a planar kinematic control strategy during gait remains after arthroscopic hip surgery for FAIS (Figure 17). However, despite no changes in the overall kinematic strategy after arthroscopic hip surgery, significant statistical differences were found in the specific joint angle contributions to the kinematic control pattern after arthroscopic hip surgery for FAIS (Table 14).

Figure 16. Three-dimensional hip joint angles during gait in the preoperative FAIS (grey dot dash) and healthy control groups (black solid line). Note that the angular covariation is more linear for the healthy controls and more planar in the preoperative FAIS group. The dotted arrow indicates 0% (heel strike), black arrow indicates 30% (mid-stance), black star indicates 60% (toe-off), and dashed arrow indicates 80% of the gait cycle (mid swing). The differences in the patterns show that hip motions were less tightly coupled in people with FAIS compared to healthy controls.
Figure 17. Three-dimensional hip joint angles during gait for the preoperative FAIS (grey dot dash) and postoperative group (grey solid line). Note that there is no difference in the angular covariation before and after surgery. The dotted arrow indicates 0% (heel strike), black arrow indicates 30% (mid-stance), black star indicates 60% (toe-off), and dashed arrow indicates 80% of the gait cycle (mid swing). The shape difference in the curves indicate differences in the joint specific contributions to the overall kinematic control strategy before and after arthroscopic hip surgery for FAIS.

Table 14. Mean (SD) contribution of each angle to shaping each principal component (PC) in the preoperative FAIS, postoperative, and control groups.

<table>
<thead>
<tr>
<th>PC</th>
<th>Hip Angle</th>
<th>Pre.</th>
<th>Post</th>
<th>Control</th>
<th>P-value (Pre. vs. Control)</th>
<th>P-value (Pre. vs. Post.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC 1</td>
<td>Flex/Ext</td>
<td>5.6 (2.7)</td>
<td>.91 (6.1)</td>
<td>.67 (15.7)</td>
<td>.352</td>
<td>.012*</td>
</tr>
<tr>
<td></td>
<td>Add/Abd</td>
<td>-10.4 (2.2)</td>
<td>-1.5 (6.3)</td>
<td>-.74 (29.2)</td>
<td>.326</td>
<td>.005*</td>
</tr>
<tr>
<td></td>
<td>IR/ER</td>
<td>4.6 (3.8)</td>
<td>2.4 (3.0)</td>
<td>.08 (13.7)</td>
<td>.796</td>
<td>.157</td>
</tr>
<tr>
<td>PC 2</td>
<td>Flex/Ext</td>
<td>-2.1 (5.1)</td>
<td>-.69 (2.3)</td>
<td>-.30 (3.9)</td>
<td>.391</td>
<td>.451</td>
</tr>
<tr>
<td></td>
<td>Add/Abd</td>
<td>.37 (1.8)</td>
<td>-.22 (2.6)</td>
<td>-.06 (.56)</td>
<td>.579</td>
<td>.665</td>
</tr>
<tr>
<td></td>
<td>IR/ER</td>
<td>1.7 (4.6)</td>
<td>.91 (3.1)</td>
<td>.36 (4.3)</td>
<td>.500</td>
<td>.654</td>
</tr>
</tbody>
</table>

Flex/Ext = Flexion/extension; Add/Abd = Adduction/abduction; IR/ER = Internal rotation/external rotation
* indicates statistical significance at p < .05
Discussion

The aim of the current study was to determine if the kinematic control strategy of the hip joint during gait is altered before and after arthroscopic hip surgery for FAIS. It was hypothesized that persons with FAIS would demonstrate a more complex kinematic control strategy than healthy controls, and that this control strategy would improve after arthroscopic hip surgery. The preoperative FAIS group did demonstrate a more complex kinematic control strategy during gait when compared to healthy controls, which was in partial support of our hypotheses. However, contrary to our hypotheses, no differences in the kinematic control strategy were observed after arthroscopic hip surgery. Interestingly, the joint angle specific contributions to the kinematic control strategy during gait were altered after surgery. The findings from this study add to the evolving evidence of altered hip joint motor control in persons with FAIS (L. E. Diamond et al., 2017). Although previous studies have identified differences in discrete kinematic parameters after hip arthroscopic surgery for FAIS, this is the first study to provide evidence of alterations in the joint specific contributions to hip kinematic control after surgery. Although the overall hip joint kinematic control during gait did not normalize after arthroscopic hip surgery, the current study demonstrates important evidence on the length of time required to re-establish normal joint control after surgery, which is consistent with previous research (J. L. Kemp et al., 2016). Therefore, clinicians should account for these long-time frames when developing postoperative rehabilitation programs for hip arthroscopy patients.

The variance proportion accounted for by the first and second principal component differed between the preoperative FAIS group and healthy controls. The variance accounted for by the first principal component was less in the preoperative FAIS group, whereas the second principal component was greater in this group. The fact that the preoperative FAIS group had significantly less variance of the first principal component and greater variance in the second
principal component indicates that this group displayed a more complex kinematic control strategy during gait demonstrated by a planar angular co-variation strategy (Courtine & Schieppati, 2004). These alterations in angular co-variation at the hip joint reflect central nervous system motor control alterations in persons with FAIS. These findings are consistent with two recent studies that also reported alterations in hip joint control during gait in people with FAIS and acetabular cartilage lesions (L. E. Diamond et al., 2017; Samaan et al., 2015). In the current study, the healthy controls demonstrated a linear pattern of angular co-variation during the stance to swing transition, exemplified by the tight coupling (i.e. linear) of the angles during this phase of the gait cycle. On the contrary, people with FAIS exhibited less coupling between the angles shown by the wider pattern during this stance to swing transition phase (Figure 16). Interestingly, Samaan and colleagues also found greater hip and knee joint coordination variability in people with acetabular chondral lesions during the terminal stance to pre-swing phase of gait (Samaan 2015). Similarly, alterations in deep hip muscle coordination was also found during early swing in persons with FAIS compared to healthy controls (Diamond 2017). The current findings are consistent with previous research in that alterations in motor control during gait seem to be most apparent during the stance to swing phase transition. Of importance is that this phase of the gait cycle is where the hip begins to move towards positions of impingement and involves a shift from eccentric to concentric activation of the hip flexor muscles. From a clinical standpoint, people with FAIS often report anterior hip pain during this transition phase of the gait cycle. Therefore, it could be argued that if this phase of the gait cycle is associated with the reproduction of hip pain then perhaps the alterations in kinematic motor control may be signify a loss of dynamic joint stability secondary to pain and joint injury (Moraiti, Stergiou, Vasiliadis, Motsis, & Georgoulis, 2010; Stergiou & Decker, 2011). These findings are important because they provide rationale for directing neuromuscular gait re-training interventions at that the stance to swing phase transition during the gait cycle (Harbourne & Stergiou, 2009).
The fact that no differences in the kinematic control strategy were found within people with FAIS before and after arthroscopic hip surgery was contrary to the study hypothesis. Perhaps this result should not be surprising considering that previous research has reported biomechanical differences at up to 24 months after arthroscopic hip surgery (J. L. Kemp et al., 2016). Interestingly, despite no change in the overall kinematic control strategy of the hip joint after arthroscopic surgery for FAIS, a substantial difference was found for the joint specific contributions to shaping the first principal component. These postoperative joint specific differences to angular co-variation occurred in the degrees of freedom for flexion/extension and adduction/abduction, which should not be surprising when the sagittal and frontal planes control demands of gait are considered (van der Krogt, Marjolein M et al., 2012). Previous gait studies after arthroscopic hip surgery for FAIS have also found kinematic differences in the sagittal plane. Rylander and colleagues (2011) reported that after hip arthroscopic surgery for FAIS, patients exhibited greater total sagittal plane hip range of motion during gait and the authors commented on the elimination of a hip flexion reversal pattern (J. Rylander et al., 2013; J. H. Rylander et al., 2011). The current study also found postoperative differences in the flexion/extension degrees of freedom contribution to the kinematic control strategy. Interestingly, the difference in the joint specific contributions to shaping PC1 of the kinematic pattern were most expressed during the stance to swing transition phase of the gait cycle. The postoperative group seems to express more of the hip joint adduction/abduction degrees of freedom shown by a wider curve transition during this phase of the gait cycle. Perhaps the preoperative to postoperative difference in this joint angle specific contribution represents the evolving optimization of joint control after arthroscopic hip surgery.

Although it remains unknow, if the postoperative changes in the joint specific contributions to the kinematic control strategy represent a trend toward normalization of kinematic control, the findings do provide some important clinical implications for postoperative rehabilitation after arthroscopic hip surgery for FAIS. The study’s findings indicate that gait
kinematic control remains altered for a prolonged period of time (> 1 year) after surgery. Although outcome studies after arthroscopic hip surgery demonstrate good to excellent results in terms of hip pain relief and improvement in patient reported function after surgery, clinicians should be aware that motor control during function may remain altered even after patients have returned to normal function (Levy et al., 2016; Menge et al., 2017; Nho et al., 2011). Since restoration of normal gait is a primary focus of rehabilitation after arthroscopic hip surgery, these results do provide support for the rationale of gait re-training exercises since alterations may exist greater than one year after surgery (Malloy, Gray, & Wolff, 2016). In addition, this study provides further evidence that central control mechanisms may be altered in people with FAIS and that these alterations may persist after surgery. The findings from this study also provide a baseline rationale to incorporate functional neuromuscular training exercise into rehabilitation for people with FAIS both before and after arthroscopic hip surgery.

Although the findings from the current study provide important insight into the kinematic control of the hip joint in persons with FAIS, several limitations must be acknowledged. The authors would like to first acknowledge that the analytic methods of PCA may be met with some debate as to what the extracted principal components represent in terms of the original kinematic data. It has been suggested that these extracted patterns of variation may represent task specific constraints on joint kinematics and not reflect the actual central control strategy for the task (Tresch & Jarc, 2009). However, multiple studies have investigated gait using these methods and have consistently identified predictable patterns that are independent of the type of multivariate analysis (Borghese et al., 1996; Ivanenko et al., 2007; Ivanenko et al., 2008). Regardless, the co-variation strategy must involve some aspect of control whether it be induced by the task or by through central control mechanisms (Ivanenko et al., 2008). Another limitation we must acknowledge is that the control group did not undergo imaging studies to identify potential hip morphology types associated with FAIS. However, previous studies have relied solely on physical examination findings like the current study (Hunt et al., 2013). Additionally, the
diagnosis of FAIS must include clinical signs and symptoms, therefore, the authors are confident that the exclusion methods used were robust for the identification of FAIS. The authors also acknowledge the small sample size of the current study, however, previous studies that have investigated people with FAIS before and after surgery have on average 12 subjects, which is similar to that of the current study (Brisson et al., 2013; J. Rylander et al., 2013; J. H. Rylander et al., 2011).
VI. CONCLUSIONS

The two aims of this dissertation were: 1) to compare clinical and biomechanical hip joint function between people with FAIS and healthy controls, and 2) to compare hip joint function before and after arthroscopic hip surgery for FAIS. Early evidence indicates that clinical and biomechanical hip joint function is altered in people with FAIS, although, this evidence is limited and inconsistent (L. E. Diamond et al., 2016; L. E. Diamond et al., 2017; L. E. Diamond et al., 2015; Freke et al., 2016; Hunt et al., 2013; Samaan et al., 2016). Additionally, despite tremendous growth in arthroscopic hip surgery for FAIS, it remains unknown if normal hip joint function is restored after surgery (Hatton et al., 2014; J. Kemp et al., 2014; Tijssen et al., 2016). FAI is considered a dynamic problem that is directly related to hip joint motion (Griffin et al., 2016). Arthroscopic surgical intervention is designed to modify hip joint structure in order to eliminate symptomatic contact during hip motion. Therefore, a better understanding of hip joint function in people with FAIS both before and after arthroscopic hip surgery is needed to improve the evaluation and treatment of this clinical hip disorder.

The goal of the first aim of this dissertation was to investigate if hip function was altered in people with FAIS when compared to healthy controls. The first study investigated if an association existed between hip muscle strength and hip joint kinetics during gait; and between hip muscle strength and patient reported outcomes measures. Reduced hip muscle strength is a common clinical sign and good measure of disease impact in people with FAIS, although, no study has investigated the potential associations between hip muscle strength and biomechanical or patient reported outcomes of function (Freke et al., 2016; Reiman et al., 2017). The current results showed a significant reduction in hip flexion muscle strength in people with FAIS compared to healthy control, which is consistent with previous literature (N. Casartelli et al., 2011). However, no difference was found for hip abduction strength, which was contrary to previous findings of similar studies (N. Casartelli et al., 2011; Harris-Hayes et al., 2014).
Interestingly, despite people with FAIS demonstrating significantly less hip flexion muscle strength when compared to healthy controls, no associations existed between hip muscle strength and hip joint kinetics during gait or patient reported outcomes. Additionally, while people with FAIS self-reported moderate functional limitations, these individuals do not exhibit alterations in gait biomechanics when compared to healthy controls. Therefore, the results of this study suggest that while hip flexion muscle strength is impaired in people with FAIS, this impairment does not appear to be related to other quantitative and qualitative measures of function. Perhaps a reason for the lack of association between maximal muscle strength and gait kinetics is that the kinetic demands of gait are not great enough to correlate with this measure. For example, the relative muscular effort during gait for the hip abductors and flexor muscles has been shown to be approximately, 40% and 71% of maximum muscle strength, respectively (van der Krogt, Marjolein M et al., 2012). Therefore, a more demanding task that requires a greater relative effort with respect to maximal muscle strength should be considered in future studies. Similarly, the lack of association between hip muscle strength and patient reported outcomes may be due to the broad nature of these functional outcome scales, which also evaluate low demand tasks that do not require maximal hip muscle effort. An interesting clinical consideration arises however if reduced hip flexion muscle strength in people with FAIS is considered in the context of prolonged activity. People with FAIS demonstrated no differences in peak hip joint kinetics during gait, which indicates they can sufficiently meet the sagittal plane kinetic demands of this task. However, since people with FAIS demonstrated less maximal hip flexion muscle strength while exhibiting similar sagittal plane peak hip joint kinetics, they do seem to operate at a greater level of relative muscle capacity (Milot, Nadeau, & Gravel, 2007; Nadeau, Gravel, Arsenault, & Bourbonnais, 1996). Perhaps operating at this greater relative capacity during a prolonged activity could result in muscular compensations and alterations in joint contact forces, which may lead to hip pain development during prolonged walking. More research is needed to directly investigate
relative muscle efforts during prolonged activity and joint contact forces during gait in people with FAI syndrome to better understand symptom development and the potential disease progression.

The next study investigated squat tasks that require terminal ranges of hip motion during single leg tasks, which are inherently more challenging than gait for people with FAI syndrome because they require motions that could potentially exacerbate hip symptoms. A recent study in people with FAI syndrome reported that when trunk and pelvis kinematics are constrained biomechanical alterations between people with FAI syndrome and healthy controls become more apparent. As such, the current study investigated if the same biomechanical results held true when the control demands of the squat task are progressed from a double to single leg. The purpose of the second study was to determine if hip joint biomechanical differences between people with FAI syndrome and healthy controls are influenced by the joint control demands of the squat task. Our findings demonstrate differences in hip joint biomechanics between people with FAI syndrome when compared to healthy controls and that these differences are influenced by the control demand of the squat task. These results support our hypothesis that a single leg squat would elicit greater differences in hip joint kinematics and kinetics between people with FAI syndrome and healthy controls.

People with FAI syndrome did not increase their peak hip extensor moment to the same magnitude as the control group when switching from a double leg to single leg squat task. Furthermore, the post-hoc analysis results show that people with FAI syndrome demonstrated smaller peak extension moments regardless of the double versus single leg demand, which is similar to a previous study (Bagwell et al., 2016). The current study also found that people with FAI syndrome demonstrate smaller peak hip abduction moments compared to controls during the single leg squat but not double leg squat task. A single leg squat task requires a greater demand on the hip abductor muscles to maintain frontal plane pelvic control as compared to a double leg squat task, therefore, these results are not surprising. Similarly, people with FAI syndrome also exhibited smaller peak adduction angles at the hip during the single leg squat but not double leg squat task. Perhaps, people with FAI syndrome tend to move into less peak hip adduction during a single leg squat as
a strategy to avoid positions associated with the symptomatic contact of FAIS. It was interesting no differences were observed for the squat performance variables of squat velocity, squat depth, and squat cycle duration as the control demand of the task was progressed from double to single leg. However, people with FAIS demonstrated slower descent velocity, ascent velocity, and a longer squat cycle duration compared to controls. These findings demonstrate a compensatory strategy regardless of the type of squat task (i.e. double vs single leg), which may also indicate that people with FAIS adopt a compensatory strategy to reduce force across the hip joint by slowing squat velocity and increasing the squat cycle duration. The combined results of this study support that people with FAIS exhibited an alteration in the hip biomechanical strategy compared to controls, which becomes more pronounced when the tasks involve terminal ranges of hip motion and require single leg control. The clinical implication of these result is that a single-leg squat is more likely to expose movement compensations in people with FAIS and may thus serve as a better tool to evaluate functional movements in this population. Additionally, the biomechanical compensation revealed during the squat tasks provide rationale for targeting rehabilitation strategies at sagittal and frontal plane muscle groups to address the control demands in these planes.

The third and fourth studies of this dissertation investigated alterations in hip function after arthroscopic hip surgery for FAIS. Both studies examined within group differences in people with FAIS before and after surgery and between-group differences for the healthy matched controls and the preoperative FAIS and postoperative groups, respectively. The purpose of the third study was to examine the effect of arthroscopic hip surgery on clinical and biomechanical hip joint function. A significant improvement in passive hip range of motion and hip flexion muscle strength was observed after arthroscopic hip surgery for FAIS with no differences in these variables between the postoperative group and matched controls. These results indicate a clear improvement in clinical measures of hip function after arthroscopic hip surgery for FAIS and are consistent with previous findings (L. E. Diamond et al., 2015; Freke et al., 2016). Not surprising,
and also consistent with previous studies, were the significant improvements in patient reported measures of function found after arthroscopic hip surgery for FAIS (Clohisy et al., 2013; Levy et al., 2016; Ng, Arora, Best, Pan, & Ellis, 2010; Nho et al., 2011). In summary, these results indicate that arthroscopic hip surgery for FAIS improves clinical hip function. However, the biomechanical results from the third and fourth study are not as clear, therefore, will be discussed in combination to provide a more comprehensive evaluation of biomechanical function before and after arthroscopic hip surgery for FAIS.

To provide a novel and comprehensive biomechanical investigation of hip joint function during gait before and after arthroscopic hip surgery for FAIS, a combination of discrete and multivariate analysis techniques were performed. The third study investigated alterations in discrete hip joint kinematic and kinetic variables, whereas the fourth study used multivariate analysis techniques to examine hip joint kinematic control during gait. Recently hip joint impulse during gait has been reported as an important biomechanical parameter for people with FAIS (Samaan et al., 2016). The third study found a significant decrease in the hip extension joint impulse and average hip extension moment during the first part of the stance phase of gait in people following arthroscopic hip surgery. Conversely, during the second part of stance phase, a significant increase in hip flexion joint moment impulse and peak hip flexion moments were found. However, despite these kinetic alterations after surgery, we did not find any within-group differences in the overall kinematic control strategy after arthroscopic hip surgery. What was interesting, however, was that the joint specific contributions to the overall kinematic control strategy were different after arthroscopic hip surgery. Specifically, alterations in the contributions of the hip flexion/extension and abduction/adduction degrees of freedom to the overall kinematic pattern differed after surgery. Although the coordination of the hip angular degrees of freedom in the sagittal and frontal plane changed after surgery, this did not translate to differences in the discrete kinematic variables during gait. Although some have argued that discrete biomechanical variable analysis (i.e. peak) is less sensitive than multivariate analysis techniques for detecting
biomechanical differences (O'Connor & Bottum, 2009), the current study did find within-group differences in discrete kinetic variables, therefore, our results do not seem to support this claim.

An interesting factor to consider when interpreting the within-group biomechanical results is that all the variables that were different in some way accounted for a temporal aspect of the data. For example, hip joint moment impulse during gait was measured as the product of the average joint moment in a direction and change in time of its application. The fourth study directly analyzed the temporal structure of the coordination of the kinematic degrees of freedom at the hip joint during the gait cycle. Recent similar studies have shown alterations in aspects of lower limb segment coordination and hip joint muscle control, therefore, perhaps the findings of the current study also indicate that aspects related to hip joint control are altered by FAIS both before and after surgery. Furthermore, since the average time from surgery in the current study 15.2 ± 3.9 months, these results also seem to indicate that a neuromuscular adjustment period continues to occur long after surgery. This is similar to previous research that has evaluated gait mechanics before and after different surgical procedures for musculoskeletal pathologies, which report alterations in gait mechanics at similar follow-up time points (Brisson et al., 2013; Leporace et al., 2012; Queen, Attarian, Bolognesi, & Butler, 2015; Yoshida, Mizner, Ramsey, & Snyder-Mackler, 2008; Zabala, Favre, Scanlan, Donahue, & Andriacchi, 2013). However, it cannot be determined if these biomechanical alterations in the current studies signify improvements in hip joint function after arthroscopic surgery for FAIS. Further longitudinal studies are required to determine the effect of arthroscopic hip surgery on improving biomechanical function of the hip joint and preventing or delaying hip OA. Modelling studies are also needed to directly measure joint contact force to determine if alterations in joint forces may signify improved or impaired joint dynamics during gait.

Although a considerable amount of literature on the patho-mechanics, diagnosis and surgical treatment of FAIS has been published; these studies have greatly exceeded quantitative studies of this clinical hip disorders impact on hip joint function. In addition to adding to the
emerging evidence on quantitative hip function in people with FAIS before and after arthroscopic hip surgery, this dissertation has also identified areas for future research that could improve the understanding of this clinical hip disorder. Although strength was not associated with biomechanical hip function during gait or patient reported outcomes in people with FAIS, the role of a strength impairment during prolonged or higher-level functions should be further explored. Perhaps, the application of musculoskeletal modelling in the context of a muscular effort paradigm could be used to determine hip muscle specific demand for an activity or simulated muscular state, such as fatigued or weakened (Milot et al., 2007; Nadeau et al., 1996; Requiao et al., 2005). In addition, modelling studies that calculate joint contact forces could help to provide context to postoperative alterations in joint kinetics in the current study. The combination of the clinical and biomechanical data from the current study could be used as inputs into musculoskeletal models, to determine individual specific levels changes in muscle and joint forces in people with FAIS. In addition, studies that investigate the association between measures of hip function, diagnostic imaging and surgical findings are needed to better understand the association between impaired hip joint function and articular damage that may contribute to early onset OA.

This set of studies demonstrated important findings on alterations in hip function in people with FAIS both before and after arthroscopic hip surgery, although, several limitations should be considered. It is acknowledged that the control group did not receive diagnostic imaging to confirm the absence of cam or pincer type FAI morphology. However, other studies have used similar methods of a physical examination to rule out underlying structural FAI (Hunt et al., 2013). Additionally, FAIS is a clinical hip disorder that includes symptoms and clinical signs, therefore, we feel the comprehensive screening examination performed by a clinical expert was sufficient for excluding potential participants with underlying cam or pincer type FAI morphology based on clinical examination alone. The relatively small sample exposes the current study to several similar limitations of generalizability. Although some of the within-group
statistical analysis did achieve sufficient power (> .90), other between group analysis were under powered (< .80). The small sample size also limited the ability to consider performing sub analyses based on the type of FAI (i.e. cam type vs. pincer type) or gender (Frank et al., 2016; Nakahara et al., 2011). Since the patho-mechanics of hip joint injury are different between cam and pincer type FAI, it could be argued that they may be associated with a type specific alteration in hip function. Also, gender differences in morphology type and outcomes after hip arthroscopic surgery have been reported, therefore, it is important for future studies to account for this in the analysis (Frank et al., 2016; Nakahara et al., 2011).

Although the current studies were exploratory, the information can be translated into the clinical management of people with FAIS. Although, hip muscle strength was not associated with kinetic gait variables or patient reported function, people with FAIS demonstrated a 31% reduction in maximal muscle strength compared to controls. Therefore, it seems rationale to implement treatments that address this physical impairment during rehabilitation. Additionally, since it was also shown that people with FAIS demonstrate a different kinematic control strategy at the hip during gait; this provides reason for the use of interventions that address neuromuscular control, in addition to interventions that target the restoration of maximal hip muscle strength. However, we do not feel the same holds true for treatments that focus on the restoration of passive range of motion. Previous studies have recommended activity modification to avoid symptomatic ranges of motion, therefore, we also suggest that this guideline is followed during treatment (Emara, Samir, Motasem, & Ghafar, 2011; Griffin et al., 2016; Yazbek, Ovanessian, Martin, & Fukuda, 2011). The results also indicate that tasks that require terminal ranges of hip motion and a single leg joint control demands may be useful during the evaluation of functional movement in the clinical setting for people with FAIS. These tasks brought about differences in hip joint biomechanics between people with FAIS when compared to healthy controls and these differences became most pronounced when the squat changed from double to single leg. Finally, after arthroscopic hip surgery, a significant improvement in clinical measures of hip function
were found. Although the current study did not document postoperative rehabilitation interventions, all patients did undergo postoperative rehabilitation that followed general postoperative arthroscopic hip surgery rehabilitation guidelines (Malloy, Malloy, & Draovitch, 2013). These guidelines did involve muscle strengthening and range of motion exercises, which clearly improve after surgery, although, it remains unknown if these improvements were associated with reductions in pain and elimination of symptomatic hip joint contact. However, this study does clearly demonstrate that even at greater than one year after arthroscopic hip surgery for FAIS, biomechanical alterations still exists during function such as gait. Therefore, clinicians should consider emphasizing the length of time it requires to normalize movement after arthroscopic hip surgery as a rationale for the importance of a home exercise program after formal discharge from rehabilitation.

Finally, the current set of studies can be summarized into three main findings: 1) clinical hip function is clearly altered in persons with FAIS and arthroscopic hip surgery significantly improves this function; 2) tasks that require terminal range of hip motion or single leg joint control demands are needed to bring about biomechanical alterations between people with FAIS compared to healthy controls; 3) gait biomechanics change after arthroscopic hip surgery for FAIS, but joint mechanics are still unlike that of healthy controls. It is evident that these alterations are present long after surgery, however, it remains unknown if these alterations represent improvements in joint function after arthroscopic hip surgery for FAIS.
VII. BIBLIOGRAPHY


