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Squat and gait biomechanics 6 months following hip arthroscopy for femoroacetabular impingement syndrome

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ABSTRACT

The purpose of this study was to (i) assess whether squat and gait biomechanical measures improve in patients with femoroacetabular impingement syndrome (FAIS) 6 months after surgery compared to pre-operative measures and (ii) compare biomechanical properties to controls without FAIS. In this prospective study, biomechanical data during a double leg squat task and gait for 15 FAIS patients and 9 controls were collected using three-dimensional motion analysis. Data were collected in the FAIS group at two-time points, pre-operatively and 6-month post-operatively following arthroscopic hip surgery, and at a single time point for the healthy controls. Independent sample's t-test were used to compare the FAIS group to the controls, and paired samples t-test were used to determine within-group differences before and after hip arthroscopy in the FAIS group. The results indicated that there were significant within-group increases for sagittal plane moment rate during the double leg squat task ($P = 0.009$) between the pre-operative and post-operative time points for the FAIS group. Between-group differences showed that FAIS patients pre-operatively exhibit slower squat velocities during the descent ($P = 0.005$) and ascent phase ($P = 0.012$) of a double leg squat when compared healthy controls. Reduced hip external rotation moments during gait ($P = 0.02$) were also found between FAIS patients pre-operatively and controls. In conclusion, alterations in hip biomechanics are present before surgery for FAIS when compared to healthy controls, and joint mechanics change 6 months after surgery. However, the biomechanical differences during a double leg squat and gait were minimal.

INTRODUCTION

Femoroacetabular impingement syndrome (FAIS) is a common cause of hip pain in young adults, and hip arthroscopy is an effective treatment for FAIS that has failed conservative treatment and rehabilitation [1–4]. A number of studies have demonstrated that hip arthroscopy for the treatment of FAIS provides significant improvements in pain, timely return to sport, high rates of achieving meaningful clinical function, and high satisfaction at short-, mid- and long-term follow-up [5–8]. To date, hip arthroscopy for FAIS has predominantly been evaluated with metrics such as patient-reported outcome scores, reported ability to return to sport, rate of revision and conversion to arthroplasty. However, several recent studies have introduced motion analysis as a new outcome measure following surgery for FAIS [9–14].

FAIS has been shown to alter hip kinematic and kinetic parameters during gait compared to matched controls [15–19]. The findings between studies have been relatively inconsistent and have demonstrated that persons with cam FAIS have decreased transverse, frontal and sagittal plane hip kinematics when compared to healthy controls [11, 13, 15, 16]. Rylander et al. (2013) reported that patients with FAIS demonstrated sagittal plane hip motion and peak hip internal rotation during stair climbing when compared to healthy controls, while Bagwell et al. (2015) demonstrated

a reduced mean hip extensor moment and peak hip internal rotation in patients with FAIS compared to controls during a double leg deep squat task [13, 20]. Moreover, many of these lower extremity gait parameters have been shown to correlate with the extent of radiographic cam and pincer morphology in FAIS patients [21]. Two studies have demonstrated improvements in gait kinematics following arthroscopic surgery for FAIS [13, 14]. Interestingly, no differences in hip kinetics were found in these cohorts after arthroscopic surgical intervention for FAIS. Several studies have also reported differences between people with FAIS and healthy controls during a double leg squat task [16, 20, 22]. However, only a single study has evaluated double leg squat biomechanics before and after surgery for FAIS, although, this cohort underwent open, not arthroscopic, surgical intervention [12]. Variables such as joint impulse and rates of force development are often considered when evaluating squat performance [23, 24]. However, previous motion analysis studies that evaluate squatting in persons with FAIS have limited analysis to discrete biomechanical variable such as peak hip joint moment or angle.

In addition to limited evidence on squat and gait biomechanics before and after arthroscopic surgical intervention, there is limited information on the short-term impact (i.e. ≤6 months post-operative) of hip arthroscopic surgery for FAIS on squat and gait biomechanics. Therefore, the primary purpose of this study was to (i) assess whether squat and gait biomechanical measures improve in patients with FAIS 6 months after surgery compared to pre-operative measures and (ii) compare biomechanical properties to controls without FAIS. A 6-month time-point was chosen as many patients are able to return to their athletic endeavors at this time [25]. We hypothesized that patients with FAIS would achieve significant improvements in squat and gait parameters by 6 months post-operatively, and that baseline differences would exists between the pre-operative time point and healthy controls. We also hypothesize that no biomechanical differences would exist between the post-operative time point and healthy controls.

A secondary purpose was to explore differences in biomechanical variables that are a function of time. These variables include: ascent and descent squat velocity, moment rate and joint moment impulse. We hypothesized that prior to surgery patients with FAIS would demonstrate slower squat descent and ascent velocities, slower moment rate and lower joint moment impulses during a squat when compared to healthy controls and that there would be no difference in these variables between controls and FAIS patients 6 months following hip arthroscopic surgery.

METHODS

Patient selection

Institutional Review Board approval was obtained prior to patient enrollment and data collection. All patients underwent pre-enrollment informed consent. Consecutive symptomatic subjects with clinical and radiographic diagnosis of FAIS, failure of conservative management and who were scheduled for hip arthroscopy between 2011 and 2013 by a single fellowship-trained surgeon were asked to participate in pre-operative gait and squat analysis. Inclusion criteria for FAIS patients included clinical signs, symptoms and radiographic findings [26], failure of at least 3 months of conservative management (including activity modification, oral anti-inflammatories and physical therapy); and ability to walk a quarter of a mile and squat without significant difficulty. Exclusion criteria consisted of hip arthroscopy for an indication other than FAIS, prior history of bilateral hip surgery, prior ipsilateral hip surgery, signs of osteoarthritis (Tonnis grade >1), hip dysplasia (LCEA < 20°) or a history of congenital hip disorders (slipped capital femoral epiphysis [SCFE], developmental hip dysplasia, etc.). Healthy control subjects had no hip pain, no history of hip or lower extremity injury or surgery, no lumbar pathology and with examination and radiographs showing no evidence of FAIS. Controls also underwent informed consent prior to participation.

Surgical technique and post-operative rehabilitation

All hip arthroscopies were performed by a single fellowship-trained hip surgeon at a high-volume academic hospital using a technique that has been well-described in the literature [27–29] Every patient underwent acetabuloplasty, femoroplasty and labral repair with T capsulotomy, dynamic fluoroscopic examination and complete capsular closure via plication. Rehabilitation started on post-operative Day 1 for all patients as previously described [30, 31]. Briefly, all patients went through a four-phase rehabilitation protocol that lasted an average of 16–18 weeks. The surgical limb was initially restricted to 20-pound foot-flat-weight-bearing during the first phase, prioritizing joint protection and soft tissue mobilization techniques. Phase 2 concentrated on normal gait maintenance, full range of motion (ROM) restoration, improvement of neuromuscular control and maintenance of pelvic and core stability. Phase 3 included single leg squats and strengthening, soft tissue and joint mobilization, and cardiovascular fitness. Phase 4 emphasized return to preinjury level of sports participation. Running on an antigravity treadmill was allowed at Week 12, and patients progressed to sport-specific activities at Week 16.

Radiographic and clinical outcome measurements

Participating patients and control subjects underwent a standard set of radiographs including anteroposterior (AP) pelvis, false profile and 90° Dunn lateral views of the hip. The AP pelvis radiograph was used to measure lateral center edge angle (LCEA) and the 90° Dunn lateral was used to measure the alpha angle [32]. Pre-operative Tönnis grade was also assessed. Post-operative radiographs were obtained following hip arthroscopy for FAIS morphology as part of routine clinical care and demonstrated normalization of radiographic FAIS morphology in all cases.

Patients completed a pre- and 6-month post-operative questionnaire that included demographic information and validated hip-specific functional outcome scores [Hip Outcome Score Sport-Specific Subscale (HOS-SS) and Activities of Daily Living (HOS-ADL) subscales] [33–37].

Functional tasks—double leg squat and gait

For the double leg squat task, participants were positioned with their surgical limb or the randomly selected limb of the control group on the force plate with their feet parallel and approximately shoulder width apart facing in the anterior direction. From an initial standing position, the participants were instructed to look forward, position their arms at shoulder height out in front of them with the elbows straight and palms facing the floor. The subjects were given verbal instructions to squat down as low as possible (Fig. 1), and to then return to an upright position while maintaining a self-selected and controlled speed for the entire squat cycle [16, 38]. Keeping the upper extremity in an anterior extended position helped maintain balance and prevented the participants from using their limbs as support. The subjects were not provided a depth target or asked to squat at a certain pace in order to promote a self-selected squat strategy. A self-selected squat strategy was used to mimic how a squat would be evaluated in a clinical setting, where minimal cues are provided during movement evaluation. If subjects had difficulty squatting, which was defined as if they reported pain or apprehension during the squat, they were instructed to only squat to a comfortable depth. Subjects were reminded to maintain even weight on both legs during the squat task. Prior to recording the trials, each participant practiced the squat a minimum of two times.

For gait tests, the subjects walked at a self-selected speed along a 6-m walkway across three concealed floor embedded force plates. The subjects wore their own shoes and completed five level walking trials per limb. The data from the surgical limb and a randomly selected limb for the control subjects were averaged for the five trials. The position of the arms was at the side for walking. A self-selected walking speed was chosen for all gait trials to mimic how gait would typically be evaluated in a clinical setting where speed is rarely controlled.

Motion analysis

All FAIS patients completed both pre-operative and 6-month post-operative motion analysis testing. Pre-operative tests were conducted within 1-month of the scheduled surgical date, while post-operative evaluations were performed within 2 weeks of the 6-month post-operative date. Control subjects completed a single motion analysis testing session. The reason for a single testing session for control subjects was secondary to the rate of attrition at our institution.

Motion analysis data acquisition

Three-dimensional position data of 28 passive retroreflective markers were collected at a sampling rate of at 100 Hz with a 12-optoelectronic camera system (Qualisys, Gothenburg, Sweden) [21, 39]. Three-dimensional force data were simultaneously sampled at 1200 Hz during gait and squat tasks with three floor-embedded force plates (Bertec, Columbus, OH, USA). Retroreflective markers were placed bilaterally on the pelvic and lower extremities at the following locations: superior point of the iliac crest, anterior and posterior superior iliac spine, L5/sacrum, the greater trochanter, anterodistal thigh, lateral and medial knee joint line, tibial tuberosity, lateral and medial malleoli, lateral most point on the calcaneus, and the second and fifth metatarsal, and unilaterally on the right shoulder to denote right and left sides (Fig. 2). The same operator placed the markers in all cases to control for marker placement. The hip-joint center was estimated to be 2 cm distal to the mid-point of a line connecting the anterior superior iliac spine to the pubic symphysis [40].

Motion analysis data processing

Data were processed used The Motion Monitor software (Innovative Sports Training Inc., Chicago, IL, USA). Kinematic data were low pass filtered with a frequency cutoff of 6 Hz. The kinetic data were down sampled by a factor of 10 to match the kinematic data sample frequency of 100 Hz. An inverse dynamics approach was used to calculate external joint moments and these moments were normalized to percent body weight times height (%BWH) [41].

Squat motion data analysis

Three trials of a double leg squat task were analyzed. The squat cycle was divided into the descent and ascent phase. This phase was defined by using the vertical position of the

Fig. 1. An instrumented participant demonstrates an unrestricted squat where they were instructed to squat as low as possible while keeping their upper limbs parallel to the floor and feet shoulder width apart.

Fig. 2. Anterior and lateral views of the 28 passive retroreflective markers used for motion analysis.

sacral marker. The initiation of the squat cycle was defined as when the mean baseline quiet stance position of the sacral marker changed by greater than two standard deviations from baseline. The termination of the squat cycle was defined as when the sacral marker position returned to the equal or less than one-half SD of the baseline sacral marker position. The squat descent phase was defined from the initiation of the squat cycle to the point where the sacral marker reached a minimum vertical position and ascent phase was defined from the point after the minimum sacral marker position to the termination of the squat cycle point.

Squat depth was quantified as the change in vertical position of the sacral marker. A custom-written MATLAB (Mathworks, Natick, MA, USA) program was used to calculate squat depth. First, the mean vertical position of the

sacral marker for the first 15 frames of squat data was calculated and used to represent baseline quiet stance. The minimum vertical position of the sacral marker was identified, and squat depth was calculated as the differences between baseline quiet stance vertical position and the minimum vertical position of the sacral marker during the squat. Squat descent and ascent velocity were calculated as the first derivatives of position of the sacral marker during the ascent and descent phases of the squat cycle and were reported in meters per second ($m\ s^{-1}$).

Squat descent and ascent velocity, sagittal plane moment rate and sagittal plane joint moment impulse for both the descent and ascent phases of the squat were determined. Sagittal plane moment rate was calculated as the slope of the joint moment curve during the descent and ascent phases of the squat. Joint moment impulse was calculated as the area under the curve of the sagittal plane moment using a trapezoidal method. Being that the entire external sagittal plane squat moment is in the direction of flexion, this will be referred to as the flexion joint moment impulse. All discrete variables were extracted and calculated from non-time normalized kinematic and kinetic waveform data. However, all squat kinematic and kinetic data were time normalized to 100 data points to represent the squat cycle for the purpose of data presentation. All calculations were performed using a custom written program in MATLAB (Mathworks, Natick, MA, USA).

Gait motion data analysis

Filtered and non-time normalized joint kinematic and kinetic waveforms were extracted for analysis from five trials of gait. Biomechanical segment parameters were determined using the position of the markers and individual anthropometric data as inputs [39]. The spatiotemporal parameter of gait speed was calculated from a virtual center of mass marker that represented a weighted average of the

center of mass of each segment included in the biomechanical model [21, 39, 42]. The gait variables of interest extracted for analysis were: peak hip joint flexion, extension and sagittal plane joint ROM and peak hip joint kinetics in all planes of motion. All discrete gait variables of interest were calculated and extracted from non-time normalized kinematic and kinetic waveform data. The kinematic and kinetic waveform data were then time normalized to 100 data points to represent the entire gait cycle.

Statistical analysis

All data were inspected to determine if parametric statistical testing was appropriate. The Shapiro–Wilk test revealed all data were normally distributed. No significant outliers were present in the data when all variables were examined with box plots. Descriptive statistics were calculated for all data. Within group comparisons for the FAIS group at the pre-operative and 6-month post-operative time point were performed using paired samples *t*-tests. Between-group comparisons for pre-operative patients and controls and post-operative patients and controls were performed using independent samples *t*-tests. Data from a single subject and the post-operative data from another subject were eliminated secondary to a technical error that lead to unusable motion analysis data. As such, the within-group comparison included $n = 12$ FAIS subjects with data from both the pre-operative and 6-month post-operative time point, and $n = 14$ FAIS subjects pre-operatively, and $n = 13$ subjects at the 6-month post-operative time point for the between group comparisons. An *a priori* alpha value of 0.05 was set to determine statistical significance. All statistical analyses were performed using SPSS software (version 22; IBM, Armonk, NY, USA). Considering there was no within-or-between-group difference in squat depth or gait speed, it was decided that these variables should not be entered as co-variates into the analysis for the other biomechanical variables. The authors chose not to control for multiple comparisons because of the exploratory nature of the study.

RESULTS

Patient demographics, radiographic parameters and patient-reported outcomes

There were no differences in age or BMI between patient with FAIS and healthy controls (Table I). FAIS patients pre-operatively, had significantly greater alpha angles and lower patient-reported outcome scores when compared to controls. A statistically significant improvement in alpha angle, HOS-SS and HOS-ADL was observed when comparing pre-operative versus post-operative score averages.

Comparison of pre-operative versus 6-month postoperative within squat kinematics among FAIS patients

FAIS patients demonstrated a greater pre-operative external peak hip extension moment during the double leg squat when compared to the 6-month post-operative time point (Pre: 0.4 ± 0.5 versus Post: 0.1 ± 0.4 N·m/BW·H; $P = 0.006$) (Table II). There were no differences in any other biomechanical variable the double leg squat task between the pre-operative and 6-month post-operative time for FAIS patients.

Comparison of pre-operative versus 6-month postoperative within gait biomechanics among FAIS patients

There were no differences in gait speed between the pre-operative and 6-month post-operative time point for FAIS patients (Pre: 1.3 ± 0.1 m·s^{-1} versus Post: 1.4 ± 0.1 m·s^{-1}, $P = 0.43$). There were no differences in any biomechanical variables during gait between the pre-operative and 6-month post-operative time point in patients with FAIS (Table II).

Comparison of squat biomechanics between FAIS versus healthy control group

Patients with FAIS pre-operatively demonstrated slower hip flexion joint angular velocity during the descent (0.4 ± 0.2 versus 0.6 ± 0.2; $P = 0.005$) and ascent (0.4 ± 0.2 versus 0.6 ± 0.2; $P = 0.012$) phase of a double leg squat when compared to healthy control (Table II). There were no differences in any squat biomechanical variable between the FAIS patients at the 6-month post-operative time point and healthy controls ($P > 0.05$ for all).

Comparison of pre-operative gait biomechanics between FAIS group versus Healthy control

FAIS patients pre-operatively demonstrated lower peak hip external rotation moments during gait compared to healthy controls (FAI: 0.6 ± 0.2 versus controls: 0.8 ± 0.2 N·m/BW·H; $P = 0.02$) (Table III). There were no between group differences were observed during gait between FAIS patients at the pre-operative or 6-month post-operative time point and healthy controls ($P > 0.05$ for all).

DISCUSSION

The primary findings of this study were that FAIS patients demonstrated a significantly decreased peak external hip extension moment during a double leg squat post-operatively compared to baseline prior to surgery. No other differences between pre-operative and post-operative measurements were found for during the double leg squat task or gait biomechanics. When comparing the FAIS to healthy control group at baseline, the FAIS group had a

Table I. Demographics, radiographic measurements and patient-reported outcomes for FAIS group at the pre-operative and 6-month post-operative time points and healthy controls

	Pre (n = 14)	Post (n = 13)	Con (n = 9)	P-value Pre versus Con	P-value Pre versus Post	P-value Post versus Con
Gender (female)	11 (84.6%)	10(76.9%)	5(55.5%)	—	—	—
Age (years)	29.4 ± 9.6	29.5 ± 9.5	27.8 ± 6.5	0.66	0.64	0.74
BMI (kg/m^2)	22.9 ± 4.8	23.0 ± 5.2	22.8 ± 3.5	0.92	0.83	0.89
Alpha angle (°)	62.3 ± 3.9	38.4 ± 4.2	51.4 ± 5.7	**0.001**	**0.001**	**0.001**
Lateral center edge angle (°)	32.0 ± 5.0	32.3 ± 4.8	32.9 ± 8.6	0.75	0.61	0.82
HOS-ADL	67.3 ± 15.1	90.6 ± 7.7	100 ± 0.0	—	**0.001**	—
HOS-SS	48.4 ± 18.0	80.8 ± 12.9	100 ± 0.0	—	**0.001**	—

Pre, pre-operative time point FAIS group; Post, 6-month postoperative time point FAIS group; Con., healthy control; F, female, M, male; BMI, body mass index; HOS-ADL, Hip Outcome Score Activity of Daily Living Subscale; HOS-SS, Hip Outcome Score Sport Specific Subscale.
Bold type indicates statistical significance at α = 0.05.

slower ascent and descent during the double leg squat. During gait, FAIS patients pre-operatively demonstrated smaller peak hip external rotation moments when compared to healthy controls. Furthermore, there were no differences in post-operative hip biomechanics during a double leg squat or gait between these two groups. While the current results indicate that hip joint biomechanics change 6 months after arthroscopic surgery for FAIS, it is difficult to draw definitive conclusions regarding whether changes indicate functional improvement in hip joint biomechanics. Further studies are needed to determine the impact of FAIS on hip joint function [13, 43, 44].

Previous studies have evaluated squat biomechanics in FAIS patients and compared them to healthy controls [19]. Diamond *et al.* compared squat biomechanics in 15 pre-operative patients to healthy controls and observed a difference in descent speed between the two groups [45]. Similar to the current study, FAIS patients demonstrated slower descent speed as compared to health individuals matched by age and sex [45]. These results are also reflected in Malloy *et al.* when patients with FAIS performed a single-leg squat more slowly than individuals without hip pain [19]. Collectively, patients with FAIS may slow their squatting speed descent in anticipation of discomfort felt in the squatting position.

The current study indicates that FAIS patients demonstrate a significantly reduced peak hip extension moment 6 months after undergoing hip arthroscopy. We also noted a statistical trend (P = 0.06) toward reduced peak hip extension angle was present. Although peak hip extension angles occurred during periods of upright stance prior to the

beginning of the actual squat, this phenomenon may help explain the difference in the peak hip extension moments between the pre-operative and post-operative time points. External moments are offset by internal moments of the antagonistic muscle groups; therefore, a lower peak external extension moment may decrease the demand on the hip flexors to reduce pain and/or discomfort. During the stance phase, hip flexor muscle activation would likely cause a more flexed posture at the hip. However, in the current study, perhaps FAIS patients standing in 2° more of hip extension after arthroscopic surgery helped facilitate a reduction in hip flexor muscle activity. The greater amount of hip extension would be driven by the hip extensor muscles (such as the *gluteus maximus* and hamstrings), and could potentially reduce the amount of activation of the hip flexor muscles, thereby leading to smaller peak hip extension moments after hip arthroscopic surgery. These data suggest physical rehabilitation needs to consider hip flexion strength to improve movement patterns following hip arthroscopic surgery. In addition to post-operative rehabilitation focusing on hip flexor strengthening, it is possible that these patients may benefit from pre-operative rehabilitation as well, since previous studies have indicated that this may have an effect on post-operative hip flexor strength in FAIS patients [46].

No other biomechanical differences between the pre-operative and 6-month post-operative time point where found, which suggests that hip squat biomechanics change very little at 6 months following arthroscopic surgery for FAIS. Similarly, Rylander *et al.* [13] reported limited improvement 1-year post-operatively for stairclimbing, an

Table II. Comparisons of the kinematic and kinetic variables during a double leg squat for the FAIS group between pre-operative and 6-month post-operative time points, and the healthy control group

	Pre	*Post*	*Con*	*P-value* *Pre versus Post*	*P-value* *Pre versus Con*	*P-value* *Post versus Con*
Kinematics						
Max. Flex. (°)	98.5 ± 19.6	99.2 ± 16.7	104.8 ± 6.2	0.95	0.37	0.35
Max. Ext. (°)	3.9 ± 5.0	2.7 ± 3.5	3.5 ± 4.2	0.06	0.83	0.62
Sagittal ROM (°)	94.7 ± 22.9	96.6 ± 17.4	101.4 ± 7.5	0.61	0.41	0.45
Descent squat velocity $(\mathrm{m \cdot s^{-1}})$	0.4 ± 0.2	0.5 ± 0.2	0.6 ± 0.2	0.08	**0.005**	0.26
Ascent squat velocity $(\mathrm{m \cdot s^{-1}})$	0.4 ± 0.2	0.5 ± 0.2	0.6 ± 0.2	0.10	**0.012**	0.22
Kinetics						
Flex. Mom. (N·m/BW·H)	−6.4 ± 1.6	−6.3 ± 1.7	−5.9 ± 0.9	0.77	0.44	0.53
Ext. Mom. (N·m/BW·H)	0.4 ± 0.5	0.1 ± 0.4	0.2 ± 0.3	**0.006**	0.50	0.51
Add. Mom. ((N·m/BW·H)	2.4 ± 1.6	1.9 ± 2.0	1.5 ± 1.7	0.06	0.21	0.61
Abd. Mom. (N·m/BW·H)	1.2 ± 0.9	1.1 ± 1.1	0.6 ± 0.4	0.71	0.08	0.20
ER Mom. (N·m/BW·H)	0.5 ± 0.5	0.4 ± 0.7	0.6 ± 0.4	0.67	0.45	0.42
IR Mom. (N·m/BW·H)	0.8 ± 0.8	0.5 ± 0.5	0.5 ± 0.7	0.18	0.26	0.94
Descent Flex. Mom. Rate (N·m/BW·H)	−2.7 ± 1.5	−3.6 ± 1.5	−3.5 ± 1.9	0.10	0.59	0.43
Ascent Flex. Mom. Rate $(\mathrm{N \cdot m \cdot BW \cdot H}) \cdot s^{-1}$	−3.5 ± 1.6	−3.9 ± 1.9	−3.1 ± 1.3	0.54	0.36	0.88
Flex. Impulse (N·m/ BW·H)·s	−12.3 ± 4.5	−9.6 ± 3.5	−11.1 ± 4.9	0.10	0.46	0.27

Data reported as mean ± standard deviation.

Pre, FAIS group pre-operative time point; Post, FAIS group 6-month postoperative time point; Con, healthy control group; Max. Flex., maximum flexion angle; Max. Ext., maximum extension angle; Sagittal ROM, total sagittal plane joint range of motion; Flex Mom., peak flexion joint moment; Ext. Mom, peak extension joint moment; Add. Mom., peak adduction joint moment; Abd. Mom., peak abduction joint moment; ER Mom., peak external rotation joint moment; IR Mom., peak internal rotation joint moment; Descent Flex. Mom. Rate, flexion joint moment rate during descent phase; Ascent Flex. Mom. Rate, flexion joint moment rate during ascent phase; Flex. Joint Impulse, flexion joint impulse during the squat cycle.

Bold type indicates statistical significance at $\alpha = 0.05$.

activity similar to squatting that involves a large ROM. In addition, Catelli *et al.* [47] observed similar findings, with no changes in squat depths at 2-years after hip arthroscopy in FAIS patients. These findings, however, are inconsistent with those from a previous study that investigated double leg squat biomechanics in FAIS patients with cam type impingement before and 1-year after surgical correction [22]. The authors reported that after surgery FAIS patient squatted to a greater mean depth compared to pre-operative measurements and demonstrated changes in ankle and knee kinematic angles. One reason for the difference between the two studies may be related to our patients

undergoing hip *arthroscopic surgery* for FAIS whereas the patients in the previous study underwent *open* surgical intervention for FAIS. This key difference in technique could lead to different recovery times, with the arthroscopic technique arguably leading to shorter post-operative recovery times. In addition, the goal of the current study was to provide information on biomechanics at an early post-operative time point (i.e. 6 months), whereas Lamontagne *et al.* [12] examined biomechanics between 8 and 32 months after surgery. This creates a wide range of post-operative recovery period for patients, which may explain the differences in a greater number of variables between

Table III. Between group comparisons of the kinematic and kinetic variables during gait for the FAIS group at the pre-operative and 6-month post-operative time points and healthy control group

	Pre	*Post*	*Con*	*P-value* Pre versus Post.	*P-value* Pre versus Con	*P-value* Post versus Con
Kinematics						
Max. Flex. (°)	18.7 ± 4.2	19.3 ± 3.9	19.8 ± 6.0	0.61	0.61	0.82
Max. Ext. (°)	−14.2 ± 6.0	−12.1 ± 3.8	−12.0 ± 4.7	0.16	0.37	0.93
Sagittal ROM (°)	32.6 ± 6.4	31.5 ± 4.8	31.8 ± 4.9	0.17	0.73	0.88
Kinetics						
Flex. Mom. (N·m/BW·H)	−4.1 ± 1.1	−3.9 ± 1.0	−4.3 ± 1.4	0.11	0.62	0.38
Ext. Mom. (N·m/BW·H)	3.6 ± 1.5	3.0 ± 1.1	3.7 ± 1.4	0.46	0.92	0.24
Add. Mom. (N·m/BW·H)	−4.9 ± 1.2	−5.1 ± 1.0	−4.6 ± 0.9	0.15	0.58	0.23
Abd. Mom. (N·m/BW·H)	1.0 ± 0.3	0.9 ± 0.3	1.0 ± 0.3	0.42	0.73	0.2
ER Mom. (N·m/BW·H)	0.6 ± 0.2	0.8 ± 0.2	0.9 ± 0.3	0.06	**0.02**	0.33
IR Mom. (N·m/BW·H)	−1.0 ± 0.3	−1.0 ± 0.2	−0.9 ± 0.2	0.53	0.5	0.7

Data reported as mean ± standard deviation.

Pre, FAIS group pre-operative time point; Post, FAIS group 6-month post-operative time point; Con, healthy control group; Max. Flex., maximum flexion angle; Max. Ext., maximum extension angle; Sagittal ROM, total sagittal plane joint range of motion; Flex Mom., peak flexion joint moment; Ext. Mom, peak extension joint moment; Add. Mom., peak adduction joint moment; Abd. Mom., peak abduction joint moment; ER Mom., peak external rotation joint moment; IR Mom., peak internal rotation joint moment.

Bold type indicates statistical significance at $\alpha = 0.05$.

both studies. This demonstrates the importance of evaluating biomechanical parameters at multiple timepoints within a single study using a single surgical procedure.

The only difference in gait biomechanics in the current study was reduced maximum hip external rotation moments during gait, which are consistent with previous studies [15, 17]. Both Hunt *et al.* and King *et al.* demonstrated a lower external rotation moment in patients with FAIS when compared to healthy controls [15, 17]. Remembering that external moments are offset by internal moments of the antagonistic muscle groups; these data suggest lower activation of the internal rotations of the hip during walking compared with controls. This compensatory mechanism may denote a strategy to prevent positions of hip internal rotation that are often reported to be painful in patients with FAIS [21, 48]. Data from Rylander *et al.* [13] support this theory as patients with FAIS demonstrated a significant reduced amount of hip internal rotation compared to health controls. However, across the literature, biomechanical alterations at the hip during gait in FAIS patients have been inconsistent with recent evidence showing no differences in gait biomechanics in people with FAIS compared to controls [11, 15, 16, 22, 49].

Perhaps the reason for inconsistency in previous studies and the minimal findings in the current study are related to the fact that gait does not involve near end ranges of hip motion, and, therefore would not be expected to reproduce symptomatic impingement at the hip joint. Additionally, although forces across the hip joint can be on average three-times body weight, this demand does not seem to bring about consistent differences in people with FAIS. Future studies should focus on the role the demand of a task plays in bringing about biomechanical differences at the hip in patients with FAIS.

Limitations

There are a number of limitations in this study that should be addressed. First, the generalizability of the study's findings may be limited due to the small sample size and the heterogeneity of the control group. However, the FAIS patients were selected prospectively from a single surgeon at a high-volume hip preservation center, therefore, our sample likely represents FAIS patients that commonly present for care. Second, the authors acknowledge the that lack of a proportional sex matching (i.e. 1:1 male:female) between the control and FAIS group does also represent a

limitation of generalizability of the current study findings. Third, although 3D motion capture remains the gold standard for biomechanical studies, wearable technologies have recently been developed that may improve the ability to collect precise movement data in the clinical or other environmental setting. The authors therefore acknowledge the clinical translation of these laboratory-based methods. Fourth, an *a priori* was not performed since, to our knowledge, no study has evaluated the change in gait and squat kinetics/kinematics in FAIS patients after undergoing surgical treatment, and therefore an effect size has not been established for any variable to calculate the necessary population size for observed power of over 80%. A *post hoc* power analysis in this study is dependent on what comparison is chosen to calculate the effect size for determining the observed power. Using the pre-operative peak external rotation joint moment average during gait and comparing it to healthy controls, the effect size (Cohen's d) is equal to 1.176697, and the observed power for a two-tailed hypothesis is 0.873. However, this power analysis may not be applicable to all the *t*-tests performed in this study, and it may be possible that some of the analysis is underpowered. In addition, the multiple comparisons on the current study increase the likelihood of committing type II error. However, there is limited information on hip biomechanics during functional tasks in FAIS patients; therefore, this study was somewhat exploratory in nature. As such, Bonferroni corrections were not applied as these data will also be used to guide variable selection in future studies to limit comparisons and reduce the risk of type II statistical error. Fifth, the authors did not account for the presence of pain during gait or squat and whether it had an effect on mechanics. Future studies may want to evaluate whether there is a correlation between pain during these actions and differences in kinematics. Finally, the lack of follow-up for the control group to account for a learning effect may also influence the results. The control group in the current study had a high rate of attrition that was outside of the authors' control which posed logistical limitations to further data collection. Future studies will involve follow-up testing of the control group and will utilize methods such as incentives to reduce the amount of attrition. Additionally, although not statistically different, there was a large range of walking speeds for gait testing, this potentially could impact moment magnitudes [50].

CONCLUSION

FAIS patients demonstrate alterations in hip biomechanics during a double leg squat task when compared to healthy controls. However, alterations during gait are minimal. Hip joint biomechanics during a double leg squat change after arthroscopic hip surgery for FAIS. Nevertheless, based on our dataset, it is difficult to determine if these alterations represent improvement. Regardless, physical therapists should remain aware that hip biomechanics 6 months after arthroscopic hip surgery may continue to demonstrate change; therefore, movement patterns should be addressed during post-operative rehabilitation.

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