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Hip kinematics and kinetics in persons with and without cam femoroacetabular impingement during a deep squat task

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ABSTRACT

Background: Previous studies have indicated that hip and pelvis kinematics may be altered during functional tasks in persons with femoroacetabular impingement. The purpose of this study was to compare hip and pelvis kinematics and kinetics during a deep squat task between persons with cam femoroacetabular impingement and pain-free controls.

Methods: Fifteen persons with cam femoroacetabular impingement and 15 persons without cam femoroacetabular impingement performed a deep squat task. Peak hip flexion, abduction, and internal rotation, and mean hip extensor, adductor, and external rotator moments were quantified. Independent *t*-tests ($\alpha < 0.05$) were used to evaluate between group differences.

Findings: Compared to the control group, persons with cam femoroacetabular impingement demonstrated decreased peak hip internal rotation (15.2° (SD 9.5°) vs. 9.4° (SD 7.8°); $P = 0.041$) and decreased mean hip extensor moments (0.56 (SD 0.12) Nm/kg vs. 0.45 (SD 0.15) Nm/kg; $P = 0.018$). In addition persons in the cam femoroacetabular impingement group demonstrated decreased posterior pelvis tilt during squat descent compared to the control group, resulting in a more anteriorly tilted pelvis at the time peak hip flexion (12.5° (SD 17.1°) vs. 23.0° (SD 12.4°); $P = 0.024$).

Interpretation: The decreased hip internal rotation observed in persons with cam femoroacetabular impingement may be the result of bony impingement. Furthermore, the decrease in posterior pelvis tilt may contribute to impingement by further approximating the femoral head–neck junction with the acetabulum. Additionally, decreased hip extensor moments suggest that diminished hip extensor muscle activity may contribute to decreased posterior pelvis tilt.

1. Introduction

Cam femoroacetabular impingement (FAI) is hypothesized to occur secondary to deformity of the femoral head resulting in a decreased offset at the head–neck junction (Beck et al., 2005; Ito et al., 2001; Pfirrmann et al., 2006). This impingement results in a less spherical femoral head and causes a shift in contact location from the acetabular cup and femoral head to the antero-superior acetabular rim and the femoral head–neck junction (Ganz et al., 2003; Ito et al., 2001). It has been proposed that cam morphology may contribute to the development of labral pathology (Johnston et al., 2008; Meermans et al., 2010; Nepple et al., 2011; Tamura et al., 2013; Tanzer and Noiseux, 2004), chondral pathology (Anderson et al., 2009; Beck et al., 2005; Johnston et al., 2008; Kaya et al., 2014; Nepple et al., 2011), and hip osteoarthritis (Agricola et al., 2013; Anderson et al., 2009; Beck et al., 2005; Gosvig et al., 2010).

While cam morphology is commonly thought to be an important factor with respect to hip pathology, many individuals with an aspherical femoral head do not report pain or exhibit pathology (Allen et al., 2009; Hack et al., 2010; Kang et al., 2010). This suggests that other factors may contribute to the development of pain and/or pathology in this population. Because impingement is proposed to occur as a result of bony abutment at end range of hip flexion or hip internal rotation (Chegini et al., 2009; Ganz et al., 2003; Ito et al., 2001), abnormal hip and pelvis kinematics could be a predisposing factor. Additionally, it is possible that hip kinematics and kinetics may be altered by the presence of FAI. Understanding predisposing factors and compensatory strategies associated with FAI may aid in the treatment of persons with this condition.

Several studies have evaluated hip and pelvis kinematics during gait in persons with cam FAI. The results of these studies are varied and have reported that persons with cam FAI exhibit decreases in sagittal (Hunt et al., 2013; Rylander et al., 2013), frontal (Brisson et al., 2013; Hunt

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Abbreviations: FAI, Femoroacetabular impingement; FABER, Flexion ABduction External Rotation test.

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et al., 2013; Kennedy et al., 2009), and transverse plane hip kinematics (Hunt et al., 2013; Rylander et al., 2013) and diminished frontal plane pelvis motion (Kennedy et al., 2009) when compared to healthy controls. A limitation of studies that have evaluated gait in this population is that maximum hip flexion during level walking is only 20–30° and does not reflect the hip flexion range thought to be related to impingement (Chegini et al., 2009).

In contrast, fewer studies have performed kinematic evaluations in persons with cam FAI during tasks involving large hip flexion excursions. Rylander et al. (2013) reported that individuals with cam FAI exhibited decreased sagittal plane hip motion and peak hip internal rotation during stair climbing when compared to healthy controls (Rylander et al., 2013). Lamontagne et al. (2009) reported a trend toward decreased total plane sagittal pelvis excursion during a maximum depth squat task in persons with cam FAI compared to healthy controls. These authors reported no differences in hip kinematics or in the pelvis angle at peak hip flexion, the position most important with respect to impingement (Lamontagne et al., 2009). Ng et al. (2015) compared several radiographic variables as well as hip kinematics during a maximum depth squat between a symptomatic group with cam morphology, an asymptomatic group with cam morphology, and an asymptomatic group without cam morphology. These authors reported that diminished total sagittal pelvis excursion during squatting significantly distinguished the symptomatic cam FAI group from the other two (Ng et al., 2015). Taken together, previous studies in this area indicate that hip kinematics may be altered during performance of end range of motion functional tasks. Furthermore, deep squatting may be a differentiating task in this population.

Although kinematic comparisons have been made between persons with cam FAI and pain-free control subject, only one study has evaluated kinematics and kinetics in persons with cam FAI during a task involving large hip flexion angles. Kumar et al. (2014) reported greater peak hip adduction and greater internal rotator moments in a preliminary investigation of persons with FAI and control subjects during a deep squat task. However, this study was limited by the small number of FAI subjects ($n = 7$) and the fact that the control group was not age or sex matched to cam FAI group. It is important to further investigate the kinematic and kinetic profiles of persons with cam FAI and matched controls during a task involving large hip flexion angles as it is not known if altered hip and pelvis kinematics are solely driven by abnormal bony morphology or altered muscular control. Previous research has shown that individuals with FAI exhibit hip muscle weakness (Casartelli et al., 2011), suggesting that impaired muscular control may be contributory to altered kinematics in this population. Evaluation of hip kinetics, in addition to kinematics, may provide indirect information regarding underlying muscular control.

The purpose of the current study was to compare three-dimensional hip kinematics and kinetics during deep squatting between persons with cam FAI and age and sex matched controls. We also were interested in comparing the sagittal pelvis and femur angles at the time of peak hip flexion between groups to determine the kinematics used to achieve hip flexion. Understanding whether the pelvis or the femur is contributing to altered kinematics may assist clinicians in developing more targeted treatment approaches. Based on previous research and the potential range of motion limitations due to bony impingement, it was hypothesized that persons in the cam FAI group would demonstrate decreased peak hip flexion, decreased peak hip abduction, decreased peak hip internal rotation, and a more anteriorly tilted pelvis at the time of peak hip flexion. It also was hypothesized that persons with cam FAI would have diminished hip moments in all three planes during this task.

2. Methods

2.1. Participants

A sample size calculation based on pilot data from our laboratory for the primary variables of interest (peak hip flexion and peak hip internal rotation) revealed that eight and 12 participants per group, respectively, were needed to achieve adequate statistical power ($\alpha = 0.05$; power = 0.90). As such, thirty participants were recruited for this study: 15 individuals with unilateral symptomatic cam FAI (nine females, six males) and 15 age and sex matched controls. Participants in the cam FAI group were recruited from two orthopedic clinics. Persons with cam FAI were eligible if they were skeletally mature (Song et al., 2012), 45 years of age or younger, and had an alpha angle measurement of greater than 50.5° (Beaule et al., 2005; Hack et al., 2010; Kennedy et al., 2009; Lamontagne et al., 2009; Notzli et al., 2002). This cut-off was chosen to be consistent with previous kinematic studies of persons with FAI (Kennedy et al., 2009; Lamontagne et al., 2009). Persons with cam FAI were excluded if they demonstrated radiographic signs of hip osteoarthritis (Notzli et al., 2002) or if they had complaints of bilateral hip pain.

Control subjects were recruited from the university community and were age matched (within 3 years) and sex matched to the subjects with cam FAI. Control subjects were excluded if there was a history of hip pain, lower extremity or low back surgery, or complaints of lower extremity or low back pain during the preceding 6 months. A clinical examination was performed on all control subjects to rule out hip pathology. Specifically, subjects were excluded if they had a positive log roll test (Martin and Sekiya, 2008), greater than 5 cm asymmetry between sides with the Flexion ABduction External Rotation test (FABER test) (Philippon et al., 2007; Vad et al., 2004), or pain with internal rotation of the hip in 90° of hip flexion (Reiman et al., 2015). Four of 19 potential control participants were excluded based on the clinical screen.

Following the clinical screen, potential control subjects underwent magnetic resonance imaging to rule out cam morphology. Subjects were excluded if they demonstrated radiographic evidence of cam FAI (alpha angle greater than 50.5° measured via axial oblique magnetic

Fig. 1. Example of the deep squat task.

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resonance images), hip dysplasia, or pincer FAI (lateral center edge angle less than 20° or greater than 40° measured via coronal pelvis magnetic resonance images) (Gold et al., 2012). Alpha angle measurements were performed by the primary author who demonstrated excellent intra-rater reliability (ICC = 0.98; standard error of the measure = 1.48°). All subjects who passed the clinical screen met the radiographic criteria to participate in the study. Prior to participation, all subjects were informed of the purpose of the study and provided written informed consent and HIPPA authorization.

2.2. Instrumentation

Three-dimensional kinematics were collected at 250 Hz using an 11-camera Qualisys motion analysis system (Qualisys AB, Göteborg, Sweden) and ground reaction forces were collected at 1500 Hz using a force plate (Advanced Medical Technology, Inc., Watertown, MA, USA). Reflective markers (11 mm diameter) were placed on the most distal aspect of the second toes, the first and fifth metatarsal heads, the medial and lateral malleoli, the medial and lateral femoral epicondyles, the greater trochanters, the iliac crests, the anterior superior iliac spines, and the L5–S1 junction. Semi-rigid plastic plates with tracking markers mounted to them were secured to the heels, shanks, and thighs. A standing calibration trial was collected to determine the segmental coordinate systems and the joint axes. All markers were then removed with the exception of the semi-rigid clusters and the markers on the iliac crests, and L5–S1.

2.3. Procedures

Prior to the biomechanical assessment, all participants completed the hip outcome score (Martin and Philippon, 2007, 2008; Martin et al., 2006). The hip outcome score subscales for activities of daily living and sports have been reported to be valid and reliable measurements for persons with acetabular labral tears and FAI (Lodhia et al., 2011; Martin and Philippon, 2008; Martin et al., 2006). Individuals in the cam FAI group also rated their current and worst pain over the previous week.

For biomechanical testing, subjects were instructed to perform a bilateral squat while standing with the involved limb on a force plate, feet shoulder width apart, and toes pointing forward. Shoulders were flexed to 90° and a step was placed behind the subject at one-third the height of the subject's tibial tuberosity (Lamontagne et al., 2009) (Fig. 1). Subjects were asked to “squat as low as possible, coming as close as possible to the step.” Subjects were instructed to maintain heel contact throughout the task. Five consecutive squats were performed at a pace of 1.33 second descent and 1.33 second ascent controlled via a metronome.

2.4. Data analysis

Using Visual 3D software (C-motion, Inc., Germantown, MD, USA), kinematic data were low-pass filtered at 6 Hz and ground reaction force data was low-pass filtered at 20 Hz using a 4th-order Butterworth filter. The middle three repetitions of the squat task were averaged for analysis. Hip kinematics were calculated as the motion of the pelvis relative to the femur. As differences in hip flexion could be due to altered motion of the femur or the pelvis, femur and pelvis angles were calculated as the orientation of the femur and pelvis segments relative to the global coordinate system. This was done to understand how hip flexion was achieved in both groups. Squat depth was quantified as the average minimum height of the L5/S1 marker normalized to leg length (defined as the height of the greater trochanter) during the squat task. Inverse dynamics equations were utilized to calculate the net joint moments. Mean moments were reported as internal moments normalized to body mass. Moment data were averaged between 20 and 80% of the squat cycle (the time frame corresponding to active squatting, as opposed to the brief period between squats when individuals were standing or transitioning from the standing position).

Table 1
Demographic and functional outcome data- mean (standard deviation).

	Control group	Cam FAI group	*P* value
Age (years)	31.9 (SD 7.6)	32.2 (SD 7.8)	0.925
Height (cm)	169.9 (SD 9.1)	171.0 (SD 9.6)	0.761
Mass (kg)	69.6 (SD 16.0)	72.1 (SD 14.7)	0.647
Hip outcome score ADL (0–100)	100 (SD 0)	65.8 (SD 15.9)	
Hip outcome score sports (0–100)	100 (SD 0)	36.5 (SD 20.8)	
VAS score (pre) (0–10 cm)	NA	3.4 (SD 2.5)	
VAS score (worst over last week) (0–10 cm)	NA	6.4 (SD 2.4)	

2.5. Statistical analysis

Variables of interest included peak hip flexion, peak hip abduction, peak hip internal rotation, maximum squat depth, mean hip extensor moment, mean hip adductor moment, and mean hip external rotator moment. Peak femur flexion and pelvis angle at the time of peak hip flexion also were evaluated. Between group differences in demographic data were evaluated using two-tailed independent *t*-tests. The kinematic and kinetic variables of interest were assessed using one-tailed independent *t*-tests. Statistical analyses were performed using PASW software (SPSS, Inc., Chicago, IL).

3. Results

The cam FAI group and the control group were similar with respect to age, height, and mass (Table 1). Participants in the cam FAI group were moderately impaired based on hip outcome scores of 65.8 ± 15.9 on the activities of daily living subscale and 36.5 ± 20.8 on the sports subscale (Table 1).

Three individuals in the cam FAI group and eight participants in the control group reached the target depth. An independent *t*-test of normalized L5/S1 minimum marker height revealed diminished squat depth in the cam FAI group compared to the control group (30% leg length (SD 18%) vs. 49% leg length (SD 14%); $P = 0.004$; $t(28) = -3.1$; 95% CI [−0.31, −0.06]). Persons in the cam FAI group exhibited decreased peak hip internal rotation during the squat task compared to the control group (9.4° (SD 7.8°) vs. 15.2° (SD 9.5°); $P = 0.041$; $t(28) = -1.8$; 95% CI [−0.4, −11.2]) (Table 2 and Fig. 2). At the time of peak hip flexion, persons in the cam FAI group exhibited a more anteriorly tilted pelvis (23.4° (SD 11.2°) vs. 12.5° (SD 17.1°); $P = 0.023$; $t(28) = 2.1$; 95% CI [1.9, 19.9]) and decreased peak femur flexion compared to the control group (83.2° (SD 19.0°) vs. 100.4° (SD 13.4°); $P = 0.004$; $t(28) = -4.1$; 95% CI [−24.3, −10.11]) (Table 2 and Fig. 3). There were no differences in peak hip flexion or peak hip abduction between groups (Table 2 and Fig. 2).

Moment data was unavailable for one participant in the cam FAI group due to technical issues. Persons in the cam FAI group demonstrated

Table 2
Kinematic and kinetic data during the deep squat task-mean (standard deviation).

	Control group	Cam FAI group	*P* value
Peak hip flexion (°)	113.0 (SD 6.7)	106.6 (SD 14.0)	0.065
Peak hip abduction (°)	11.9 (SD 6.8)	11.8 (SD 6.2)	0.961
Peak hip internal rotation (°)	15.2 (SD 9.5)	9.4 (SD 7.8)	0.041*
Pelvis angle at peak hip flexion (°)	12.5 (SD 17.1)	23.4 (SD 11.2)	0.023*
Femur angle at peak hip flexion (°)	100.4 (SD 13.4)	83.2 (SD 19.0)	0.004*
Mean hip extensor moment (Nm/kg)	0.56 (SD 0.12)	0.45 (SD 0.15)	0.018*
Mean hip adductor moment (Nm/kg)	0.09 (SD 0.17)	0.12 (SD 0.11)	0.633
Mean hip external rotator moment (Nm/kg)	0.05 (SD 0.10)	0.06 (SD 0.10)	0.626

* Significant P value.

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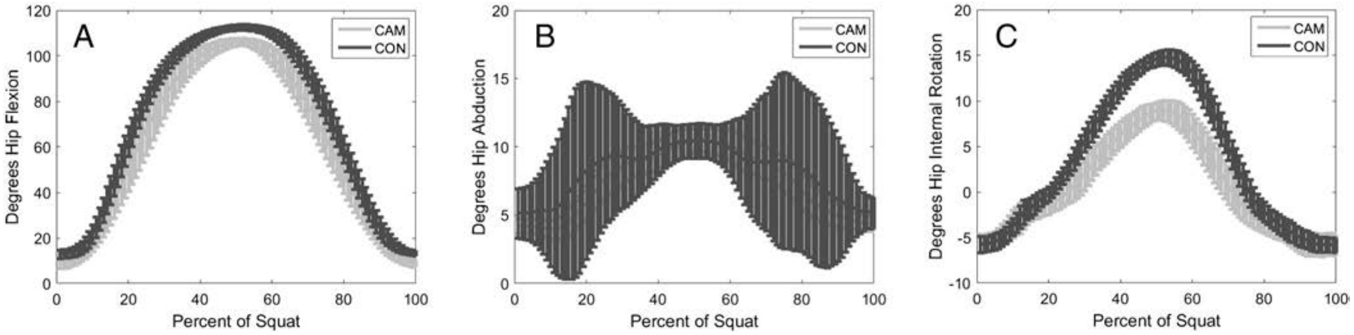

Fig. 2. Comparison of hip kinematics between groups. A) Sagittal plane, B) frontal plane and C) transverse plane.

decreased mean hip extensor moments compared to the control group (0.45 Nm/kg (SD 0.15 Nm/kg) vs.0.56 Nm/kg (SD 0.12 Nm/kg); $P = 0.018$; $t(27) = -2.2$; 95% CI [-0.2, 0.0]). There were no differences in the mean hip adductor moment or mean hip external rotator moment between groups (Table 2 and Fig. 4).

4. Discussion

Persons with cam FAI demonstrated altered kinematics and kinetics during deep squatting compared to the control group. Specifically, the cam FAI group exhibited diminished squat depth, decreased peak hip internal rotation, and a more anteriorly tilted pelvis at the time of peak hip flexion. The cam FAI group also exhibited decreased mean hip extensor moments compared to the control group. In general, these differences were consistent with our proposed hypotheses.

On average, the cam FAI group had approximately 6° less hip internal rotation compared to the control group. This finding is consistent with Rylander et al. (2013) who reported decreased peak hip internal rotation in persons with cam FAI during stair climbing (Rylander et al., 2013). Conversely, Lamontagne et al. (2009) and Kumar et al. (2014) found no difference in peak hip internal rotation during deep squatting in persons with cam FAI compared to control subjects (Kumar et al., 2014; Lamontagne et al., 2009). Lamontagne et al. (2009) used a similar study design and patient population as the current study. In the study by Kumar et al. (2014) study participants were instructed to squat to a depth of 25% of the participant's height (approximately 80° peak hip flexion, compared to greater than 100° in the current study). Therefore, the conflicting results may be a reflection of the heterogeneity of this population or may be the result of different squat depths evaluated.

Despite the diminished peak hip internal rotation observed in the cam FAI group, there was no difference in the mean hip external rotator moment between groups. Therefore, it can be indirectly inferred that the observed decrease in peak hip internal rotation may be due to factors other than external rotator muscular control. This suggests that bony abutment may have contributed to the diminished hip internal rotation observed in the cam FAI group. This seems logical given previous reports of a relationship between cam morphology and diminishing passive hip internal rotation range of motion (Audenaert et al., 2012; Notzli et al., 2002; Wyss et al., 2007). Additionally, a previous finite element modeling study by Jorge et al. (2014) demonstrated the extent to which cam morphology can limit hip internal rotation. These authors found that at 90° of hip flexion, internal rotation was limited to 2.8° in the presence of a large cam deformity (alpha angle 98°) (Jorge et al., 2014). A post-hoc analysis of the data obtained in the current study revealed that the degree of cam morphology and peak hip internal rotation during the deep squat task were inversely correlated ($R = 0.48$; $P = 0.04$). We postulate that cam morphology may be limiting hip internal rotation in persons with cam FAI during squatting. However, further research is needed to confirm this hypothesis.

Persons with cam FAI also exhibited diminished posterior tilt of the pelvis as participants approached their maximum depth, resulting in a relatively more anteriorly tilted pelvis at the time of peak hip flexion compared to the control group. This finding is consistent with Lamontagne et al. (2009), who reported a trend toward decreased total sagittal pelvis motion during a maximum depth squat in persons with cam FAI. These authors suggested that decreased posterior motion of the pelvis was the primary explanation for this trend (Lamontagne et al., 2009). Decreased posterior pelvis tilt (or a more relatively anteriorly tilted pelvis) would be expected to increase impingement between the femur and the acetabulum, particularly during a task involving deep hip flexion. The observed decrease in posterior pelvis tilt in persons with cam FAI may be the result of several factors including decreased lumbopelvic mobility, guarding, or altered hip extensor muscle activation. With respect to the latter, a significant decrease in the mean hip extensor moment was found in the cam FAI group. One possible explanation for the decreased hip extensor moment could be decreased utilization of the hip extensors to accomplish the squat task. In particular, decreased activation of the gluteus maximus and/or hamstring muscles could have contributed to the lack of posterior pelvis tilt. Hypothetically, relative posterior tilt of the pelvis during this phase of squatting would limit the potential for impingement in the presence of cam morphology. Unlike diminished hip internal rotation, which may be the result of hip

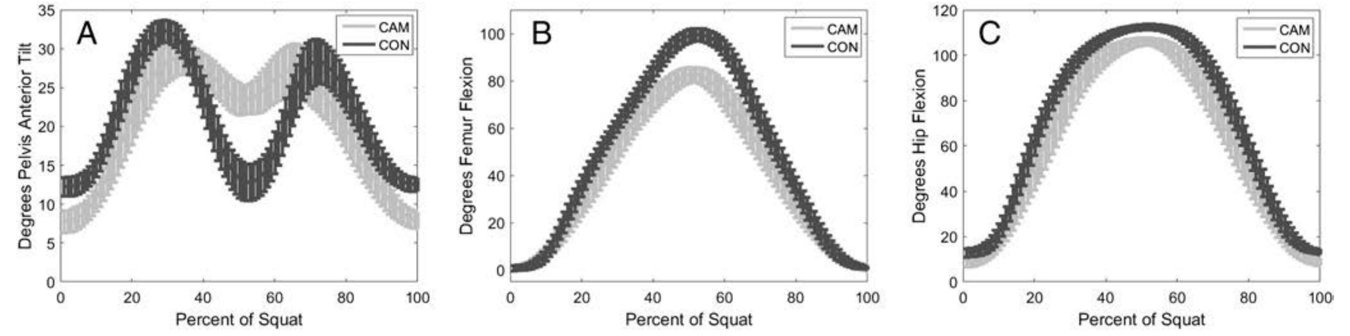

Fig. 3. Comparison of sagittal plane kinematics between groups. A) Pelvis, B) femur and C) hip.

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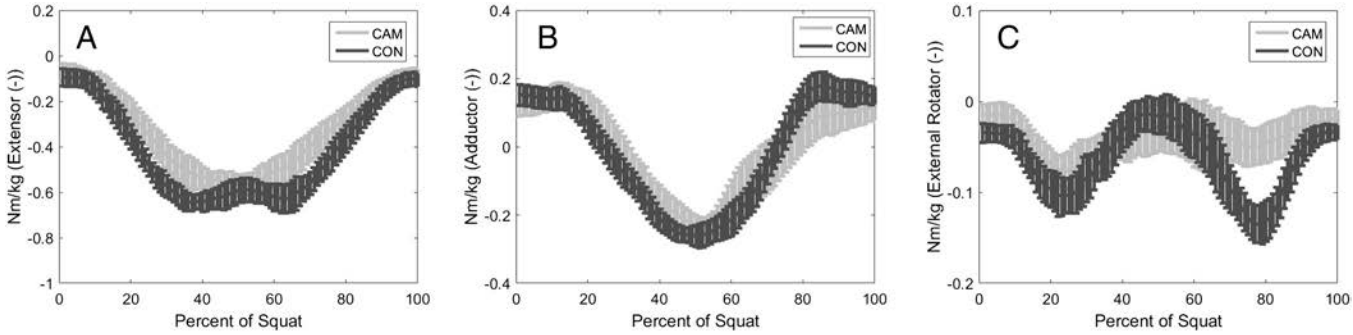

Fig. 4. Comparison of hip kinetics between groups. A) Sagittal plane, B) frontal plane and C) transverse plane.

morphology, altered pelvis motion potentially could contribute to pathology in this population. It should be noted however, that cause and effect relationships cannot be determined based on our study design.

Despite the decrease in posterior pelvis tilting and relatively more anteriorly tilted pelvis at the time of peak hip flexion observed in persons with cam FAI, there was no difference in peak hip flexion. This finding is consistent with previous investigations of squat kinematics in this population (Kumar et al., 2014; Lamontagne et al., 2009). In the current study, the relative contribution of the pelvis and the femur in achieving peak hip flexion differed between groups. At the time of peak hip flexion persons with cam FAI exhibited decreased femur flexion (almost an 18° decrease in femur flexion compared to the control group). The decreased femur flexion coupled with greater relative anterior pelvis tilt resulted in the similar hip flexion angle. Reduced femur flexion in the cam FAI group may be relevant from a functional standpoint as the inability to flex the femur may result in difficulty preforming tasks such as sitting down in a low chair.

Despite significant differences in sagittal and transverse plane kinematics and kinetics, there were no differences in peak hip abduction or mean hip adductor moments between groups. Similarly, previous kinematic investigations have failed to identify frontal plane differences in this population during squatting (Lamontagne et al., 2009) or stair climbing (Rylander et al., 2013). Given the bilateral nature of squatting, this finding is not surprising. It is likely that unilateral tasks involving greater frontal plane demands would be more informative of frontal plane control.

Taken together, the results of our study suggest that clinical interventions to improve posterior tilt of the pelvis and external rotation of the femur may protect against impingement. Previous studies have reported hip muscle weakness in persons with FAI (Casartelli et al., 2011; 2012). In particular, the gluteus maximus may be important given its ability to posteriorly tilt the pelvis and externally rotate the femur. Future research should examine the effect of hip strengthening or neuromuscular retraining of hip extensor muscles on hip and pelvis biomechanics, pain, and function in this population.

The current study has several limitations. First, all participants in the cam FAI group were symptomatic prior to testing; therefore, it is not possible to determine if altered kinematics or kinetics were the cause or effect of pain. In either scenario, however, it could be argued that the kinematics displayed may be perpetuating pathology in persons with cam FAI. Second, electromyographic and strength data were not collected as a part of this study. Future studies should obtain such data to allow for a more complete understanding of the underlying differences in hip and pelvis kinematics and kinetics. Third, an alpha angle cut-off of 50.5° was used as the inclusion criteria for the cam group. Due to this dichotomous cut-off, it is possible that there was an anatomical overlap with respect to group assignment; however, we feel that this possibility was minimized by the small measurement error (1.48°). Lastly, the diminished squat depth in the cam FAI group complicates interpretation of the kinematic and kinetic variables examined in our study. It is possible that variable squat depth could have affected these variables.

5. Conclusions

Persons with cam FAI exhibit altered hip and pelvis kinematics and kinetics during a deep squat task. Specifically, persons with cam FAI demonstrated decreased hip internal rotation, decreased posterior pelvis tilt during squat descent (resulting in a more anteriorly tilted pelvis at peak hip flexion), and diminished hip extensor moments. The decreased hip internal rotation observed in persons with cam femoroacetabular impingement may be the result of bony impingement. Furthermore, the decrease in posterior pelvis tilt may contribute to impingement by further approximating the femoral head–neck junction with the acetabulum. Additionally, decreased hip extensor moments suggest that diminished hip extensor muscle activity may contribute to decreased posterior pelvis tilt.

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