Published in final edited form as:

J Biomech. 2015 August 20; 48(11): 2879–2886. doi:10.1016/j.jbiomech.2015.04.022.

In-vivo Hip Arthrokinematics during Supine Clinical Exams: Application to the Study of Femoroacetabular Impingement

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Abstract

Visualization of hip articulation relative to the underlying anatomy (i.e., arthrokinematics) is required to understand hip dysfunction in femoroacetabular (FAI) patients. In this exploratory study, we quantified in-vivo arthrokinematics of a small cohort of asymptomatic volunteers and three symptomatic patients with varying FAI deformities during the passive impingement, FABER, and rotational profile exams using dual fluoroscopy and model-based tracking. Joint angles, joint translations, and relative pelvic angles were calculated.

Compared to the 95% CI of the asymptomatic cohort, FAI patients appeared to have decreased adduction and internal rotation during the impingement exam and greater flexion and less abduction/external rotation in the FABER exam. During the rotational profile, only one patient (most severe deformities) demonstrated considerable rotation deficits. Contact between the labrum and femoral head/neck limited motion during the impingement exam, but not the rotational profile, in all participants. Substantial pelvic motion was measured during the impingement exam and FABER test in all participants. Femoral translation along any given anatomical direction ranged between 0.69–4.1 mm.

These results suggest that hip articulation during clinical exams is complex in asymptomatic hips and hips with FAI, incorporating pelvic motion and femur translation. Range of motion appears to be governed by femur-labrum contact and other soft tissue constraints, suggesting that current computer simulations that rely on direct bone contact to predict impingement may be unrealistic. Additional research is necessary to confirm these preliminary results. Still, dual fluoroscopy data may serve to validate existing software platforms or create new programs that better-represent hip arthrokinematics.

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

Conflict of interest statement

SKA has a financial relationship with Pivot Medical and Arthrocare Corp, outside the submitted work. CLP has a financial relationship Biomet, outside the submitted work.

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Introduction

Femoroacetabular impingement (FAI) is considered a common cause of hip pain and may initiate osteoarthritis (Ganz et al., 2003). Morphologically, FAI presents as femoral head/neck asphericity (cam), acetabular overcoverage (pincer), or both (mixed). Functionally, a diagnosis of FAI is substantiated with a history of functional limitations due to hip pain and clinical examination findings such as reduced rotation, pain during the impingement exam, and/or a positive flexion-abduction-external-rotation (FABER) exam (Figure 1) (Audenaert et al., 2012a; Ganz et al., 2003; Philippon et al., 2007a; Philippon et al., 2007b). However, both morphological and functional abnormalities may be subtle in FAI patients. Further, with a high prevalence of radiographic findings of FAI in asymptomatic individuals (Kang et al., 2010; Kapron et al., 2011; Laborie et al., 2011; Omoumi et al., 2014; Philippon et al., 2013) it is difficult to discern which anatomical features are truly pathological.

Accurate measurements of hip kinematics, displayed with respect to the underlying 3D anatomy (i.e., arthrokinematics), would enable us to understand the impingement process. Specifically, observations of hip articulation relative to the underlying morphologic abnormalities may isolate those anatomical features that restrict range of motion in FAI patients. However, there is a paucity of data to quantify in-vivo hip arthrokinematics in hips with both normal and abnormal anatomy. Video tracking of markers adhered to the skin of FAI patients has identified gross reductions in hip ROM during activities of daily living (Hunt et al., 2013; Kennedy et al., 2009; Lamontagne et al., 2009; Rylander et al., 2013). However, soft tissue artifact and inaccuracies in estimating the hip joint center limit the applicability of skin marker tracking to determine what dictates terminal range of motion and how the anatomic deformities of FAI contribute to restrictions. Further, direct visualization of hip arthrokinematics is not possible with this technique as motions are typically observed with respect to a generically scaled 3D model. Computer simulations have incorporated subject-specific anatomy of the joint, reconstructed from CT or MR images, to estimate motion deficiencies. However, these models have applied generic or inaccurate kinematics and assume a fixed center or axis of rotation for the femur (Audenaert et al., 2011; Bedi et al., 2012; Chang et al., 2011; Tannast et al., 2007). In addition, ROM has either been estimated in these simulations from limits caused by direct bone-on-bone collision in the model (ignoring the contributions of surrounding soft tissue), or from magnetic-based tracking systems that are subject to the same errors as skin markers.

Dual fluoroscopy (DF) and model-based tracking (MBT) provide an accurate method to measure arthrokinematics in-vivo without the limitations of standard skin-marker motion capture. Previously, we have applied DF and MBT to measure femur-labrum contact patterns during the impingement exam (Kapron et al., 2014a). In the current exploratory study, we used DF and MBT to better understand the hip arthrokinematics of asymptomatic subjects and patients with varying presentations of FAI during the impingement exam as well as the FABER exam and rotational profile. Specifically, we visualized hip motion and quantified hip joint angles, translation of the femoral head relative to the acetabulum, and pelvic motion to elucidate the subtle articulating behavior of the hip joint during motions likely to put the hip into a terminal position.

Materials and Methods

Participants. The asymptomatic subjects and FAI patients (collectively referred to as “participants”) recruited in the study herein were previously analyzed using DF and MBT to estimate femur-labrum contact patterns at the terminal position of the supine impingement exam (Kapron et al., 2014a). Briefly, with IRB approval (#51053), six individuals (two females/four males, 26 ± 3.7 years old, BMI 21 ± 1.2 kg/m²) were enrolled as the “asymptomatic cohort”. Each individual in this cohort reported no history of hip pain, and on gross inspection of an anteroposterior (AP) screening radiograph, did not present with hip deformities or signs of OA.

Three individuals scheduled for hip arthroscopy for treatment of symptomatic FAI with the co-author, SKA, were enrolled in the study. Each patient reported left hip pain for greater than two years, had positive impingement and FABER exams, and demonstrated radiographic findings of FAI on AP and frog-leg lateral films (Kapron et al., 2014a). Patient 1 (male, 25 years old, BMI 26.2 kg/m²) presented with a substantial pistol-grip cam deformity (alpha angle 80°) and mildly shallow socket (lateral center edge angle 20°). Patient 2 presented with protrusio (excessively deep acetabulum) (lateral center edge angle 42°), a downward sloping sourcil, a large pincer groove, and large bony prominence at the anterolateral femoral neck (alpha angle 71°). Patient 3 presented with mixed FAI, including acetabular overcoverage (lateral center edge angle 45°), femoral head asphericity (alpha angle 70°) and a pincer groove at the anterolateral femoral neck.

CT Arthrography and 3D Reconstruction. CT arthrograms were acquired of all participants using a Siemens SOMATOM Definition Scanner (Siemens Medical Solutions USA, Inc, Malvern, PA, USA), as described previously (Henak et al., 2014; Kapron et al., 2014a). Images of the hip were upsampled to 3x resolution to reduce staircase artifact (Harris et al., 2012) and then segmented in Amira (5.4.1, Visage Imaging, San Diego, CA) to create 3D surface reconstructions of the pelvis, femur, and labrum.

Dual Fluoroscopy and Model-Based Tracking. Using a validated DF system protocol (positional and rotational tracking error less than 0.48 mm and 0.58°, respectively (Kapron et al., 2014b)), three clinical exams (the impingement, FABER, and rotational profile in neutral flexion exams) were performed during continuous dual fluoroscopy with a high speed digital camera capturing video at 100 Hz. Each participant was positioned supine on a radiolucent table with the left hip centered in the combined field of view (FOV) of both fluoroscopes. A wide seatbelt-like strap was secured around the anterior superior iliac spines and the table to ensure the pelvis remained in the FOV during exams. An orthopaedic surgeon, SKA, manipulated the hip through the three exams as is done in the clinic (Figure 1). Two trials were completed for each exam. Total fluoroscopy time for each participant averaged 28.4 ± 3.88 s, which included initial positioning and all exam trials. Fluoroscopy energy settings were manually adjusted for each participant; average fluoroscope tube voltage and current were 79 ± 7.0 kVp, 3.0 ± 0.37 mA, respectively.

Model-based tracking was used to determine the position and orientation of the hip during each exam as described previously (Bey et al., 2006; Kapron et al., 2014b). After

establishing the relative perspective of the two fluoroscopes with images of a calibration frame, digitally reconstructed radiographs (DRRs) were generated from ray trace projection through the CT data of each bone. The user manually rotated and translated the DRRs to provide an initial estimate of the bone pose relative to the fluoroscope images. The MBT software maximized the normalized cross-correlation between the DRR and fluoroscopic image pixel intensities to determine the in-vivo position and orientation of the bones in each frame of interest.

Joint Angles and Translations. Anatomical coordinate systems representing the pelvis and femur were established following International Society of Biomechanics (ISB) recommendations, with modifications to standardize selection of bony landmarks from the CT reconstructions (Kapron et al., 2014b; Wu et al., 2002). Joint angles were calculated following the Grood-Suntay convention (Grood and Suntay, 1983).

For each trial, the position and orientation of the pelvic anatomical coordinate system in the first and last frames were averaged to define neutral. The transformation between this neutral coordinate system and the pelvic anatomical coordinate system in each frame was calculated to study relative pelvic angles. Angles derived from the transformation matrix followed the Grood-Suntay convention, with the proximal segment represented by the neutral coordinate system and the distal segment represented by the pelvic anatomical coordinate system of each frame (Grood and Suntay, 1983).

To facilitate comparisons between participants, joint and pelvic angles were linearly interpolated between time points of interest. For the impingement exam, these time points included the first peak in flexion and the point of maximum internal rotation in flexion (terminal position, Figure 1A). For the FABER exam, the first peak of flexion and the saddle point in flexion (representing the terminal figure-4 position, Figure 1B) were used. The terminal positions at maximum internal (Figure 1C) and maximum external rotation (Figure 1D) were selected for the rotational profile.

Angular repeatability between the two trials of each participant was calculated at the terminal points of each exam. Specifically, the difference in the three joint angles between the two trials was found for each individual and the differences were averaged for each terminal position across all nine participants.

Joint translation was defined as the vector from the pelvic joint center to the femoral joint center. This vector was projected onto each of the pelvic coordinate axes (recalculated for the current frame) to obtain medial/lateral, anterior/posterior, superior/inferior translations. The range of translation for each participant was calculated using the minimum and maximum values along each axis.

For all kinematic outcome measures, results were averaged between the two trials of each exam for each patient or asymptomatic subject. Data were presented as the average and 95% confidence intervals of the six asymptomatic subjects, while patient data were presented individually. During each exam, the labrum surface was assumed to transform rigidly with the pelvis. For each trial of the impingement exam, the frame of initial contact between the labrum and anterosuperior femoral head/neck was identified on the joint angles plot.

Results

At the terminal position of each exam, the average difference in joint angles between the two trials of each participant was less than 4° (Table 1). Internal/external rotation and abduction/adduction were slightly more repeatable than flexion/extension.

During the impingement exam, all three FAI patients exhibited adduction and internal rotation angles outside the 95% confidence interval (CI) of the asymptomatic controls (Table 2, Figure 2). Contact between the labrum and femoral head/neck limited maximum internal rotation and adduction during the impingement exam in both the asymptomatic cohort (Video 1) and FAI patients (Video 2).

All participants achieved greater internal rotation during the rotational profile than the impingement exam (Table 2). For the rotational profile, Patients 1 and 3 appeared to have similar internal rotation angles when compared to the asymptomatic cohort (Figure 3). In contrast, patient 2 achieved 21° less internal rotation than the mean of the asymptomatic subjects. In both the FAI patients (Video 3) and asymptomatic cohort (Video 4), maximum internal rotation did not appear to be limited by contact between the labrum/acetabulum and femur (Figure 4).

Both the asymptomatic cohort (Video 5) and FAI patients (Video 6) achieved greater external rotation in the terminal, figure-4 position of the FABER test compared to the rotational profile (Table 2). In the figure-4 position, the FAI patients required greater flexion and/or achieved less abduction and external rotation compared to the 95% CI of the asymptomatic cohort (Figure 5).

Substantial pelvic motion was measured during the impingement exam (Figure 2) and FABER test (Figure 5), with less pelvic motion noted during the rotational profile (Figure 3). As the hip was flexed during the impingement exam, the pelvis immediately began to tilt posteriorly. However, pelvic rotation and obliquity did not change substantially until after initial contact was made between the labrum and femur (Figure 2) in both the asymptomatic cohort (Video 1) and FAI patients (Video 2).

Translation along any given anatomical direction of the femoral joint center relative to the pelvic joint center ranged between 0.69–4.1 mm, for all study participants and exams (Figure 6). Translations appeared greater during the FABER test and impingement exam than the rotational profile. Patient 1 exhibited the greatest translation in the anterior-posterior and inferior-superior directions during the FABER test.

Discussion

An accurate measurement technique that affords visualization of motion relative to the underlying anatomy is required to comprehensively understand how FAI alters hip function. The limitations and assumptions of previous methods to quantify or predict hip kinematics have prohibited direct measurements of hip articulation. In this study, DF and MBT were employed to accurately quantify and visualize 3D in-vivo hip arthrokinematics of asymptomatic subjects and FAI patients during passive clinical exams. As an exploratory

study with a small sample size, it was only possible to analyze data using descriptive statistics. Collectively, we found hip articulation to be a complex process during clinical exams, incorporating pelvic motion and translation of the femoral head. Our data suggest direct femur to labrum contact limits ROM during the impingement exam, but that other factors must limit ROM during the rotational profile. Future research will need to examine hip arthrokinematics in a larger cohort to confirm these preliminary findings. Overall, FAI patients demonstrated decreases in relevant joint angles when individually compared to the asymptomatic group. Patient 2 had an extremely deep acetabulum and the least ROM during all exams, including restrictions in internal rotation during the rotational profile. Despite having a mildly shallow socket that could afford supraphysiologic motion, Patient 1 achieved less ROM during the impingement exam. It is therefore possible that the cam-type deformity present in Patient 1 caused motion restrictions that were independent from acetabular morphology. It is important to note that while the three joint angles were reported during each exam to describe the overall position of the joint, flexion angles during the impingement exam and flexion and adduction angles during the rotational profile were not expected to and indeed did not vary substantially across participants due to the method to perform each exam (Figure 1). However, all three joint angles are relevant when analyzing the terminal position of the FABER test as increased flexion and/or decreased abduction/external rotation could result in a greater distance between the exam table and lateral border of the patella.

Femoral translations appeared larger during the FABER test and impingement exam than the rotational profile in all participants. This difference was possibly due to subtle hinging or subluxation at the terminal position of the FABER and impingement exams, which was not readily apparent during the rotational profile, where the labrum was not contacted (Figure 3). In skin marker motion analysis and existing simulations of impingement, the center of rotation (COR) is assumed to be fixed. Using our technique, it was not necessary to assume a static COR. With actual femoral head translations measured in our study on the order of 0.69–4.1 mm (upwards of ~10–20% of the radius of the femoral head (Lombardi et al., 2011)), it is possible that use of a static COR leads to erroneous measurements and unrealistic visualizations of hip joint articulation.

Despite being secured to the exam table, the pelvis moved substantially during all clinical exams in all participants. The finding that pelvic obliquity and tilt did not change substantially until the labrum was contacted provides evidence that the impingement exam indeed places the hip into terminal range of motion. In contrast, there was no femur-labrum contact during internal rotation in neutral flexion. Accordingly, pelvic motion was minimal during the rotational profile (Figure 4). It is possible that other soft-tissue restraints, such as the hip capsule or ischiofemoral ligament (Fuss and Bacher, 1991; Martin et al., 2008), limit internal rotation during neutral flexion. Nonetheless, we believe it will be important to measure pelvic motion in future kinematic studies of FAI patients. Specifically, reports suggest that upwards of 23% of FAI patients experience lower back and sacroiliac pain (Clohisy et al., 2009; Philippon et al., 2007b). Knowledge of pelvic motion in FAI patients could provide an explanation for the source of lower back pain in these individuals.

As the first study to use DF and MBT to measure in-vivo hip joint angles during supine clinical exams, it is not possible to directly compare the findings of our study with prior work. However, using computer simulations, maximum internal rotation during the impingement exam was estimated at $27.9 \pm 7.4^\circ$ in control subjects and $12.3 \pm 6.5^\circ$ in cam FAI patients (Audenaert et al., 2012b). These estimates are greater than the rotation measured in the present study (Table 3), possibly due to different flexion and adduction angles (angles not reported in (Audenaert et al., 2012b)) and the absence of soft tissue restraints. In another simulation of 18 cam FAI patients, maximum internal rotation in 85° flexion and 20° adduction was $5.7 \pm 15.7^\circ$. Despite less flexion and more adduction, this estimate of internal rotation is similar to the restrictions identified in the three patients in the present study (Bedi et al., 2013). However, in the study by Bedi et al., maximum external rotation in neutral flexion was $52.7 \pm 15.9^\circ$, almost 20° greater than all participants in our study herein (Bedi et al., 2013). Also, in the simulation by Bedi et al., maximum range of motion was estimated from bone on bone collision; in external rotation this resulted in direct collision between the greater trochanter and ischium. To date, we have not found direct scientific evidence to corroborate the presence of direct bone-on-bone collision between the trochanter and ischium during external rotation. Finally, Audenaert et al. evaluated maximum rotation in neutral flexion with an electromagnetic tracking system. For control subjects, mean internal and external rotation were 34.1° and 38.4° , respectively, similar to that reported in the present study for our asymptomatic group (Audenaert et al., 2012a).

This study has limitations that warrant discussion. Only three FAI patients were included, prohibiting statistical comparisons between groups. However, our primary purpose was not to compare and contrast gross ROM results between groups, but to understand hip articulation in the context of terminal range of motion. As a whole, the heterogeneous group of subjects evaluated herein enabled us to identify features of hip articulation that appear to be common across morphology – substantial translation of the femoral head relative to the acetabulum (at large range of motion during the FABER and impingement exams), pelvic tilt after femur-labrum contact (during the impingement exam), and the absence of direct bone-on-bone contact (during any exam). Next, asymptomatic subjects were enrolled based only on an absence of grossly abnormal deformities and osteoarthritic changes and no history of hip pain; specific radiographic cutoff values were not used. Nevertheless, as there is little consensus regarding which cutoffs define ‘normal’ morphology, we believe the exclusion criterion were valid for this exploratory study.

In summary, we found that hip articulation is a complex process, not only in FAI patients, but also in asymptomatic subjects. The observation that femur-labrum contact limited range of motion during the impingement exam, but not the straight-legged rotational profile, supports the utility of the impingement exam to assess terminal range of motion and provides evidence that pain experienced by FAI patients with labral damage during the impingement exam may result from strain to the nociceptive labrum. Key findings of femoral translation and pelvic motion call into question the validity of prior simulations used to predict impingement that rely on the assumption of a stationary pelvis, and a constant COR (Audenaert et al., 2011; Bedi et al., 2012; Chang et al., 2011; Tannast et al., 2007). The accurate kinematics measured in this study could serve to validate existing computer simulations or be used to develop additional software packages that more accurately

represent the dynamic path of hip articulation, including a translating joint center, soft-tissue restraints, and pelvic motion. Data could also serve as boundary conditions in finite element models investigating labrum and cartilage mechanics. By analyzing a larger cohort of asymptomatic and pathological hips, we may better understand how abnormal anatomy influences ROM in the hip. For example, correlating anatomical measurements to hip arthrokinematics may facilitate a more objective approach to define cut-off values used to diagnose FAI. Data could also be used to evaluate the accuracy of skin marker motion analysis and the sensitivity of joint angle measurements to different methods to estimate the hip joint center. Finally, use of DF and MBT may explain the source responsible for decreased hip ROM during load-bearing activities that has been previously studied using skin-marker-motion analysis. Analysis of load-bearing activities may also provide insight into compensatory mechanisms by the contra-lateral hip in patients with unilateral FAI.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We thank Blake Zimmerman and Justine Goebel for assistance with segmentation and model-based tracking.

Sources of Funding

The authors would like to thank the LS Peery Discovery Program in Musculoskeletal Restoration for funding related to this project.

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Figure 1.

A) Terminal position of the impingement exam, maximum internal rotation in adduction and ~90° flexion. For this exam, the clinician moves the hip from neutral to ~90° flexion, then simultaneously adducts and internally rotates the hip to the terminal position. Clinically, this test would be considered positive if pain was elicited. B) Terminal position of the FABER exam, the figure-4 position. For this exam, the clinician flexes and then abducts and externally rotates the hip to position the lateral malleolus above the contralateral knee, creating the figure-4 position. Clinically, this test would be considered positive the distance between the exam table and the lateral border of the patella was decreased compared to the contralateral limb. C) Maximum internal rotation during the neutral-flexion rotational profile. D) Maximum external rotation during the rotational profile. For the rotational profile, the clinician rotates the hip in an approximately neutral flexion and adduction

position. Clinically, decreased internal or external rotation compared to the contralateral limb or normal reference ranges would be considered significant.

Figure 2.

Joint angles (left column) and pelvic angles (middle column) of asymptomatic subjects and FAI patients during the impingement exam. Angles presented as mean $\pm$ 95% confidence intervals for asymptomatic cohort. Vertical grey bar represents frame of initial contact between labrum and femoral head/neck, average $\pm$ 1 standard deviation for all participants. Right column: anterior view of asymptomatic subject at time points of interest: a) neutral (start of the exam), b) approximate midpoint of flexion, c) maximum flexion, d) maximum internal rotation in flexion (terminal position).

Figure 3.

Joint angles (left column) and pelvic angles (middle column) of asymptomatic subjects and FAI patients during the rotational profile. Angles presented as mean $\pm$ 95% confidence intervals for asymptomatic cohort. Right column: anterior view of asymptomatic subject at time points of interest: a) neutral (start of the exam), b) maximum internal rotation (terminal position), c) neutral, d) maximum external rotation (terminal position).

Figure 4. Superolateral view of position of Patient 3 at maximum internal rotation in neutral flexion (left). Black box highlights enlarged region shown at right. Internal rotation of the femur did not appear to be limited by contact to the acetabulum or labrum (inner border highlighted by dashed line).

Figure 5.

Joint angles (left column) and pelvic angles (middle column) of asymptomatic subjects and FAI patients during the FABER test. Angles presented as mean $\pm$ 95% confidence intervals for the asymptomatic cohort. Right column: anterior view of asymptomatic subject at time points of interest: a) neutral (start of the exam), b) maximum flexion, c) approximate maximum adduction, d) terminal figure-4 position.

Figure 6.

Range of femoral head translation in the three anatomical directions for each clinical exam. Boxes represent mean $\pm$ 95% confidence intervals for the asymptomatic cohort. Patient results plotted individually. Med-Lat: Medial-Lateral. Post-Ant=Posterior-Anterior. Inf-Sup=Inferior-Superior.

Table 1

Repeatability of the Clinical Exams: Difference in Joint Angles at the Terminal Exam Position between the Two Trials

Exam	Flexion/Extension	Abduction/Adduction	Internal/External Rotation
Impingement Exam	$2.2 \pm 2.2^\circ$	$2.0 \pm 1.6^\circ$	$2.4 \pm 1.7^\circ$
Internal Rotation	$1.6 \pm 1.6^\circ$	$1.4 \pm 1.5^\circ$	$0.6 \pm 0.48^\circ$
External Rotation	$1.4 \pm 1.7^\circ$	$1.0 \pm 0.89^\circ$	$1.3 \pm 0.85^\circ$
FABER	$3.9 \pm 1.9^\circ$	$3.2 \pm 3.8^\circ$	$0.96 \pm 1.1^\circ$

Table 2

Joint Angles (in Degrees) of Asymptomatic Cohort and FAI Patients at the Terminal Position of Each Exam

Exam	Angle	Asymptomatic Cohort Mean (95% CI)	Patient 1	Patient 2	Patient 3
Impingement Exam	Flexion (+)	93 (86 to 100)	94.7	107.0	97.1
	Adduction (+)	11 (6.7 to 14)	5.7	2.2	3.2
	Internal Rotation (+)	19 (15 to 24)	11.6	7.8	9.7
Internal Rotation	Flexion (+)	14 (5.1 to 23)	22.1	17.4	18.2
	Adduction (+)	2 (-1.4 to 5.4)	5.1	4.2	-2.2
	Internal Rotation (+)	35 (28 to 41)	38.3	13.4	38.4
External Rotation	Flexion (+)	14 (3.7 to 25)	18.2	19.2	16.3
	Adduction (+)	-7.2 (-10 to -4.8)	-10.2	-3.1	-7.0
	Internal Rotation (+)	-36 (-45 to -28)	-27.6	-7.9	-29.4
FABER Test	Flexion (+)	39 (30 to 48)	48.1	74.5	58.0
	Adduction (+)	-37 (-41 to -32)	-34.7	-26.7	-27.3
	Internal Rotation (+)	-48 (-56 to -40)	-36.5	-23.2	-41.6

CI = Confidence interval