Hip and Pelvis Movement Patterns in Patients With Femoroacetabular Impingement Syndrome Differ From Controls and Change After Hip Arthroscopy During a Step-Down Pivot-Turn Task

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Background: Alterations in hip kinematics during functional tasks occur in positions that cause anterior impingement in patients with femoroacetabular impingement (FAI) syndrome. However, tasks that do not promote motions of symptomatic hip impingement remain understudied.

Purpose: To compare movement patterns of the hip and pelvis during a step-down pivot-turn task between patients with FAI and controls as well as in patients with FAI before and after hip arthroscopy.

Study Design: Controlled laboratory study.

Methods: Three-dimensional motion capture was acquired in 32 patients with FAI and 27 controls during a step-down pivot-turn task. An FAI subsample (n = 14) completed testing 9.2 ± 2.0 months (mean ± SD; range, 5.8-13.1 months) after hip arthroscopy. Statistical parametric mapping analysis was used to analyze hip and pelvis time series waveforms (1) between the FAI and control groups, (2) in the FAI group before versus after hip arthroscopy, and (3) in the FAI group after hip arthroscopy versus the control group. Continuous parametric variables were analyzed by paired *t* test and nonparametric variables by chi-square test.

Results: There were no significant differences in demographics between the FAI and control groups. Before hip arthroscopy, patients with FAI demonstrated reduced hip flexion ($P = .041$) and external rotation ($P = .027$), as well as decreased anterior pelvic tilt ($P = .049$) and forward rotation ($P = .043$), when compared with controls. After hip arthroscopy, patients demonstrated greater hip flexion ($P < .001$) and external rotation of the operative hip ($P < .001$), in addition to increased anterior pelvic tilt ($P \leq .036$) and pelvic rise ($P \leq .049$), as compared with preoperative values. Postoperatively, the FAI group demonstrated greater hip flexion ($P \leq .047$) and lower forward pelvic rotation ($P = .003$) as compared with the control group.

Conclusion: Movement pattern differences between the FAI and control groups during the nonimpingement-related step-down pivot-turn task were characterized by differences in the sagittal and transverse planes of the hip and pelvis. After hip arthroscopy, patients exhibited greater hip flexion and external rotation and increased pelvic anterior tilt and pelvic rise as compared with presurgery. When compared with controls, patients with FAI demonstrated greater hip flexion and lower pelvic forward rotation postoperatively.

Clinical Relevance: These findings indicate that hip and pelvis biomechanics are altered even during tasks that do not reproduce the anterior impingement position.

Keywords: hip arthroscopy; femoroacetabular impingement syndrome; movement patterns; statistical parametric mapping, hip biomechanics

Femoroacetabular impingement (FAI) syndrome is a common cause of hip pain in the young adult population.[11]

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This condition has been described as a clinical hip disorder that is motion related and presents with hip symptoms, clinical signs, and imaging findings indicative of cam and/or pincer bone morphology.[11,31] Clinically, the combined hip motions of hip flexion, adduction, and internal rotation are termed the *position of anterior impingement*, as these combined motions have been shown to reproduce symptoms in patients with FAI syndrome attributed to abnormal contact between the femur and acetabulum.[11]

Biomechanical research in FAI syndrome is driven by the scientific premise that direct bony contact occurs at near end ranges of hip motion. As such, previous research has found differences in hip and pelvis biomechanics between people with FAI syndrome and healthy controls during tasks such as step-ups and double- and single-leg squats, which involve near end range or combined hip motions.[8,22,23] However, research evaluating walking has revealed alterations in joint kinematics between patients with FAI and controls in positions not associated with mechanical impingement.[16,18,21,33] A recent in vivo biomechanical study using dual-plane fluoroscopy found that hip joint kinematics were altered during the terminal stance and preswing periods of gait when the hip was in a position of extension.[18] This finding refutes the premise that joint biomechanics are altered because of direct bony mechanical contact at near end ranges of motion in people with FAI syndrome. Consequently, further biomechanical research that investigates tasks that do not promote symptomatic mechanical impingement in people with FAI syndrome are necessary to better understand movement alterations in this motion-related hip disorder. Additionally, given the complexity of the biomechanical alterations in this hip disorder, innovative methods of investigating these alterations in movement patterns are needed to improve this understanding.

In recent years, innovative data analysis techniques, such as statistical parametric mapping (SPM), have been applied in biomechanics research to better understand biomechanical alterations in clinical populations.[24,26,28,29,33] Techniques such as SPM allow for the comparison of the entire movement pattern, as opposed to comparing only single discrete points selected from the continuous time series—for example, peak hip flexion angle during a squat cycle.[26,27,29] SPM is based on random field theory, which relies on data being smooth and occurring within a given phase of interest, such as joint kinematics during a squat or gait cycle.[26,27] The 2 major advantages of SPM are (1) the ability to preserve the entire waveform for comparison and (2) the elimination of the need to conduct multiple univariate comparisons that potentially increase type I error risk.[29] Therefore, the application of SPM to analyze biomechanical data during a task that does not involve motions thought to cause symptomatic mechanical impingement represents an innovative way to advance the understanding of movement alterations in people with FAI syndrome.

The step-down pivot turn is a novel task that involves a movement pattern of hip extension and external rotation and constitutes a nonimpingement-related task. However, hip extension and external rotation place stress on the surrounding soft tissues of the hip, which may be irritated or damaged in cases of FAI, such as the joint capsule and acetabular labrum.[4,10] Therefore, studying nonimpingement-related tasks such as the step-down pivot turn will advance the understanding of the role that movement may play in the diagnosis and treatment of FAI syndrome. Additionally, investigating changes in movement patterns before and after hip arthroscopy will provide new information on the impact of surgical treatment on quantitative outcomes of hip function in patients with FAI.

The purpose of this study was to compare movement patterns of the hip and pelvis during a step-down pivot-turn task between patients with FAI syndrome and healthy controls and within a subsample of patients before and after hip arthroscopy. We hypothesized that patients with FAI would have reduced hip and pelvis dynamic range of motion (ROM) during the step-down pivot-turn task when compared with healthy controls and that after hip arthroscopy, patients with FAI would demonstrate increased dynamic ROM at the hip and pelvis as compared with presurgery.

METHODS

Study Design and Power Analysis

The present study is part of an ongoing motion capture laboratory-based study with a prospective and observational design. An a priori power analysis was conducted to determine the adequate sample size to fulfill between- and within-subject comparisons. An anticipated effect size of 0.91 was used to calculate the sample size and was based on pilot data from the step-down pivot-turn task and previously published motion capture research.[22,23] It was determined that 44 participants (n = 44) with an equal allocation ratio (FAI syndrome, n = 22;

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Ethical approval for this study was obtained from Rush University Medical Center (ORA No. 10011901-IRB01-CR13).

controls, n = 22) were needed to detect the desired effect at a power of 0.9 and alpha level of 0.05. A subsample of 12 participants with FAI syndrome was needed to fulfill the within-subject comparisons at this power. Institutional review board approval was obtained before enrollment and initiation of any data collection. All participants provided informed consent, while minor assent was obtained for participants aged <18 years before enrollment. Participants between 14 and 45 years of age were approved to participate in this study.

FAI Syndrome and Hip Arthroscopy: Patient Selection

FAI syndrome diagnosis was made by either a primary care sports medicine physician or a fellowship-trained orthopaedic surgeon (S.J.N.) who specializes in hip preservation from the same institution. The diagnosis criteria were based on an international consensus statement for FAI syndrome: hip pain and symptoms lasting >3 months, a positive anterior impingement test result during physical examination, and radiographic evidence of cam and/or pincer morphology.[11] A Dunn view radiograph was used to examine the alpha angle, where an angle >55° indicates cam morphology.[2,11] Pincer morphology was evaluated on an anterior-posterior pelvis radiograph and defined by any of the following radiographic signs: a lateral center-edge angle (LCEA) >40°, presence of crossover sign, or acetabular index <0°.[32] All patients diagnosed with FAI syndrome did receive nonoperative treatments in combination or isolation, such as physical therapy, oral anti-inflammatory drugs, intra-articular injection, and/or activity modification. As inherent to the treatment of FAI syndrome, patients underwent a trial of nonoperative measures before undergoing surgery if indicated, which was the same time when enrollment and kinematic testing were performed.

Patients diagnosed with FAI syndrome were excluded for any of the following reasons: radiographic evidence of osteoarthritis (Tönnis grade >1); history of chronic low back pain or reports of low back pain within the 6 months before study enrollment[5,30]; history of surgery to the indexed or contralateral hip; history of any systemic disorders (musculoskeletal, neurologic, cardiorespiratory, integumentary, or endocrine system) that would prevent participation in the study tasks; and history of a developmental hip disorder, such as Legg-Calvé-Perthes disease, slipped capital femoral epiphysis, or developmental hip dysplasia. All patients with FAI syndrome who met the study inclusion criteria for the current study were prospectively recruited for participation from December 2018 to December 2019.

We also evaluated a subsample of patients with FAI who underwent hip arthroscopy. These patients elected to undergo hip arthroscopy after failed nonoperative treatment for hip pain, physical impairments, and functional limitations secondary to FAI. All patients underwent hip arthroscopy with the senior orthopaedic surgeon (S.J.N.) of this study. The subsample postoperative data collection for this study was conducted between June 2019 and August 2020.

Control Participant Selection

A convenience sample of control participants was prospectively recruited between July 2019 and November 2020. Control participants were eligible for study participation if they had no complaints of hip pain or clinical signs of FAI syndrome, defined as a positive anterior impingement test result. All control participants were screened for clinical signs of FAI syndrome before motion testing. Additionally, a subset of 10 control participants underwent a magnetic resonance imaging (MRI) scan to evaluate for asymptomatic cam- or pincer-type morphology. It was determined that a single control participant demonstrated an underlying cam morphology; however, none of the MRI-scanned controls had pincer morphology or undiagnosed borderline or frank acetabular dysplasia based on an LCEA <25°.

Three-Dimensional Motion Capture Data Acquisition

Kinematic position data were sampled at 100 Hz using a 20-camera motion capture system (NaturalPoint). Kinetic data were captured using 2 force plates (Bertec Corp) at 1000 Hz. A marker set consisting of 60 reflective markers was attached to anatomic landmarks of the trunk, pelvis, and lower extremities segments (thigh, shank, foot), and rigid clusters of markers were also attached to the bilateral thighs and shanks.[23] A static standing trial was collected to define segment parameters using all 60 markers as described elsewhere.[23]

Step-Down Pivot-Turn Task

Although the step-down pivot-turn task promotes loading in hip extension and external rotation, which is a nonimpingement-related movement pattern, the loaded nature of this task simulates a type of “pivoting activity” that may be performed in daily living and sport activity. All participants began by standing with feet shoulder-width apart on top of a 20.3-cm platform with the toes positioned approximately 2.5 cm from the front of the step (Figure 1A). In the initial contact phase, participants stepped down from the platform, leading with the symptomatic/operative extremity, and made contact with the force plate (Figure 1B); they then immediately pivoted 90° in the contralateral direction with respect to the symptomatic/operative extremity (ie, right operative hip = right step-down, pivot turn to left) (Figure 1C) and continued walking 4 or 5 steps to the side of the laboratory space (Figure 1D). For the control group, a randomly selected limb was chosen for analysis. All participants were asked to practice the task once before official data collection to familiarize them with the task. Participants then completed 3 trials, with a 15- to 30-second rest period between trials.

Data Processing and Analysis

Visual3D software (C-Motion) was used to process all kinematic and kinetic data. Raw marker position data were

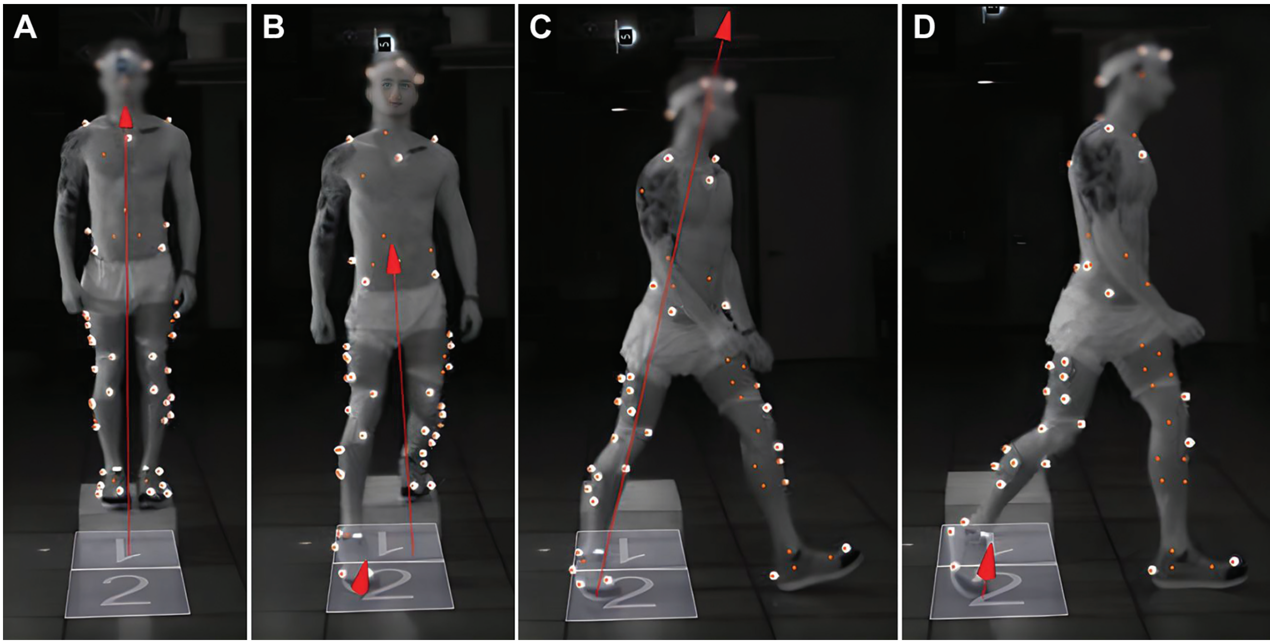

Figure 1. Demonstration of the step-down pivot-turn task in a patient with right-sided femoroacetabular impingement. (A) The participant begins with feet shoulder-width apart on top of the platform. (B) Initial contact phase: the participant steps off the platform with the operative limb leading and makes initial contact with the force plate. (C) Pivot-turn phase: the participant loads the limb and pivots 90° in the contralateral direction. (D) Toe-off phase: the participant unloads the limb, as indicated by toe-off, and continues walking toward the wall to complete the task. The red arrows indicate the vertical ground reaction force vector to indicate heel strike and toe-off.

filtered and joint centers estimated as previously described in the literature.[22,23] Hip joint angles were calculated as the relative angle between the femur and pelvis using x-y-z planes (mediolateral, anteroposterior, and longitudinal). A Cardan rotation sequence was applied such that flexion-extension occurred about the x-axis, abduction-adduction about the y-axis, and internal-external rotation about the z-axis. Pelvic motion was described in reference to a laboratory coordinate system, where anterior-posterior pelvic tilt, contralateral pelvic drop and rise, and contralateral pelvis forward and backward rotation occurred about the x-y-z axes of the laboratory, respectively. Hip flexion, hip adduction, hip internal rotation, posterior pelvic tilt, contralateral pelvic rise, and contralateral backward rotation were positive values, whereas hip extension, hip abduction, hip external rotation, pelvic anterior tilt, contralateral pelvic rise, and contralateral pelvic forward rotation were negative values.

The force plate was used to define the step-down pivot-turn task cycle, which was defined as a single frame before initial contact with the force plate (Figure 1B) through pivot turn (Figure 1C) to toe-off (Figure 1D). All trials from each participant's non–time-normalized waveforms were extracted from the step-down pivot-turn task cycle and time normalized to 100 data points using a custom script in MATLAB (Version 18; MathWorks). The time-normalized hip and pelvis angle waveforms were used for subsequent statistical analysis.

Patient-Reported Outcome Measures

Patients with FAI syndrome completed the following patient-reported outcome measures during the preoperative visit and at a mean 9 months postoperatively: Hip Outcome Score–Activities of Daily Living, Hip Outcome Score–Sports Subscale, International Hip Outcome Tool–12, and visual analog scale for pain. The 2 Hip Outcome Score subscales and International Hip Outcome Tool–12 have shown adequate psychometric properties for use in young and middle-aged active adults with hip-related pain.[12]

Hip Arthroscopy: Surgical Technique and Postoperative Rehabilitation

All hip arthroscopies were performed by a single fellowship-trained hip surgeon (S.J.N) who specializes in hip arthroscopy. An interportal capsulotomy was performed to establish access to the central compartment. Once established, procedures were performed as indicated and included acetabuloplasty, femoroplasty, labral debridement or repair (depending on condition), and chondral lesion debridement to stable margins. In all patients, a vertical T-capsulotomy was performed to access the peripheral compartment and assess cam deformity. An arthroscopic burr was used to resect abnormal bony morphology, and intraoperative fluoroscopy and a dynamic

TABLE 1
Pre- and Postoperative Physical Therapy for Patients Who Underwent Hip Arthroscopy

Physical Therapy	Mean ± SD
Preoperative	
No. of sessions	7.9 ± 7.5
Duration, wk	6.1 ± 8.1
Postoperative	
No. of sessions	32.5 ± 12.7
Duration, wk	22.8 ± 13.9

hip examination were performed to confirm adequate resection. The T-capsulotomy was repaired in all patients using a suture-shuttling device starting at the base of the vertical portion, followed by the interportal segment.[3]

The postoperative rehabilitation guidelines were based on 3-phase movement control progression.[19] A standardized set of criteria was used to advance progressions through the 3 phases (Supplemental Table S1, available separately). However, it must be recognized that phases of any progression are not mutually exclusive during the rehabilitation process. Postoperative rehabilitation was not formally monitored as part of this study for the patients who underwent hip arthroscopy, yet a summary of pre- and postoperative physical therapy received by this subsample is included in Table 1.

Statistical Analysis

All demographic variables were compared between groups with independent-samples *t* tests or chi-square analysis based on variable type. Paired-sample *t* tests were used to compare patient-reported outcome scores within the FAI group undergoing hip arthroscopy. All bivariate statistical analyses were conducted using SPSS software (Version 26; IBM).

One-dimensional SPM was used to compare the continuous joint angle time series for the hip and pelvis in all planes of motion. SPM applied to 1-dimensional angle time series waveform uses a statistical inference-based procedure to determine a critical *t*-threshold based on a new data distribution created from the residuals between trial joint angle waveforms and the grand mean waveform.[26,27,29,33] This new data distribution represents a new random field where a suprathreshold clustering technique is applied to generate a critical *t*-threshold from this new distribution, as opposed to a Gaussian distribution, which is most commonly applied in univariate statistical inference testing.[27] The new critical *t*-threshold generated from the new data distribution is equivocal to a univariate *t*-threshold as in an independent- or paired-sample *t* test model but allows for the comparison of the entire angle time series between or within groups. In the current study, hip joint and pelvis angle time series were compared between the FAI and control groups, in patients with FAI before versus after hip arthroscopy, and between patients with FAI after hip arthroscopy and controls. All SPM analyses were performed in MATLAB (open source code provided by spm1d.org using the spm1D 0.4 package; Version M.0.4.8). The a priori α level to indicate statistical significance was set at 0.05 for all SPM and group demographic discrete variable analyses.

TABLE 2
Demographics for the FAI and Control Groups[a]

	Control (n = 27)	FAI (n = 32)	*P*
Age, y	27.0 ± 7.0	30.0 ± 7.0	.106
Body mass index, kg/m^2	22.6 ± 3.1	22.9 ± 2.5	.659
Female sex	18 (66.7)	20 (62.5)	.739
Left side affected/tested	14 (51.9)	17 (53.1)	.922

[a]Data are reported as mean ± SD or No. (%). FAI, femoroacetabular impingement.

RESULTS

Patients and Controls

Fifty-nine participants were included in the final analyses: 32 patients with FAI syndrome and 27 healthy controls. Group breakdown revealed no significant differences in age, body mass index, or sex distribution between the FAI and control groups (Table 2). In the FAI group, 28 patients had isolated cam-type morphology, 3 had mixed-type morphology, and 1 had isolated pincer-type morphology. The mean ± SD Dunn alpha angle and LCEA were 64.4° ± 11.8° and 31.1 ± 6.4°, respectively.

FAI Subgroup: Patients Who Underwent Hip Arthroscopy

A subsample of 14 patients with FAI completed pre- and postoperative motion analysis testing, with follow-up testing at a mean 9.2 ± 2.0 months (range, 5.8-13.1 months). Eight patients were female, representing 57% of the postoperative sample. After surgery there was a significant reduction in the femoral alpha angle ($P < .001$) and a significant increase ($P < .05$) in all postoperative patient-reported outcome measures, indicating improvement in patient-reported function after surgery (Table 3).

Hip and Pelvis Time Series Comparisons

Patients Versus Controls. There were significant differences in sagittal plane hip joint motion ($P = .041$) from initial contact to early pivot turn (0%-15%) between the FAI and control groups. Differences in sagittal plane pelvic motion ($P = .049$) were found just before toe-off in the final 92% to 100% of the stance phase (Figure 2, A and D). These sagittal plane movement pattern differences were characterized by overall less hip joint flexion at the beginning of the task and less anterior pelvic tilt at the end of the task in the FAI group as compared with the control group. Patients also demonstrated differences in the

TABLE 3
Demographics of Patients Who Underwent Hip Arthroscopy (n = 14)[a]

	Preoperative	Postoperative	*P*
Age, y	27.9 ± 7.6	28.7 ± 7.2	—
Body mass index, kg/m^2	22.7 ± 2.6	22.7 ± 3.0	.998
Angle, deg			
Femoral alpha	67.9 ± 11.6	38.7 ± 3.5	**<.001**
Lateral center edge	30.7 ± 4.6	30.7 ± 4.3	.894
Score			
HOS-ADL	73.6 ± 12.0	92.1 ± 5.8	**<.001**
HOS-SS	45.4 ± 23.2	68 ± 28.2	**.001**
iHOT-12	40.1 ± 17.3	84.9 ± 13.3	**.008**

[a]Data are reported as mean ± SD. Bold *P* values indicate statistically significant difference between pre- and postoperative values ($P < .05$). The dash indicates no statistical comparison. HOS-ADL, Hip Outcome Score–Activities of Daily Living; HOS-SS, Hip Outcome Score–Sports Subscale; iHOT-12, International Hip Outcome Tool–12.

transverse plane at the hip (*P* = .027) and pelvis (*P* = .043). These differences in movement patterns occurred at the end from 82% to 100% and 78% to 100% of the task, respectively (Figure 2, C and F). No differences in frontal plane movement patterns were found at the hip and pelvis between patients with FAI and controls (Figure 2, B and E).

Patients With FAI Before Versus After Hip Arthroscopy. After hip arthroscopy, there were changes in the sagittal hip plane throughout the cycle (0%-100%; $P < .001$), with patients demonstrating significantly greater hip flexion postoperatively. Additionally, changes were noted in the pelvic sagittal plane movement patterns at the beginning (*P* = .033) and end (*P* = .036) of the step-down pivot-turn cycle. After hip arthroscopy, more motion in the direction of anterior pelvic tilt from initial contact (0%-32%) of the cycle was shown and remained more anteriorly tilted from 72% to 100% of the cycle after surgery as compared with presurgery (Figure 3, A and D). The changes in the hip and pelvis sagittal plane demonstrated that the overall hip movement pattern after surgery was consistent with a more anteriorly tilted pelvic position. Similarly, changes in pelvic frontal plane motion at initial contact (0%-5%; *P* = .049) and in the early part of the task (12%-41%; *P* = .018) were found after hip arthroscopy. No differences in hip frontal plane movement patterns were identified after surgery. Conversely, in the transverse plane, movement pattern changes occurred at the hip joint from 15% to 100% of the cycle ($P < .001$), although no changes in pelvic movement patterns were observed. The postoperative hip changes were characterized by overall more hip external rotation during the task after surgery.

Patients With FAI After Hip Arthroscopy Versus Controls. As compared with healthy controls, patients with FAI after hip arthroscopy exhibited differences in the hip sagittal plane of movement toward the middle (*P* = .007) and end (*P* = .047) of the task. Patients with FAI had greater hip flexion during the pivot-turn phase (33%-88%) and toe-off phase (92%-98%) postoperatively (Figure 4A). There were no postoperative differences noted in the frontal or transverse planes of the hip between the FAI and control groups. At the pelvis, patients with FAI demonstrated reduced pelvis forward rotation postoperatively as compared with the controls from the pivot-turn to toe-off phase (*P* = .003; 49%-100%). No significant differences were noted in the pelvis sagittal or frontal planes.

DISCUSSION

When compared with healthy controls, patients with FAI syndrome demonstrated significantly less overall hip flexion and anterior pelvic tilt. Additionally, patients with FAI had lower overall hip external rotation, driven by less overall contralateral pelvis forward rotation than controls. The movement pattern findings of lower hip flexion, anterior pelvic tilt, and forward pelvic rotation during a step-down pivot turn are in agreement with previous research investigating in vivo hip kinematics during walking in patients with cam-type FAI versus healthy controls.[1,18] After surgery, movement pattern changes were characterized by greater hip flexion and anterior pelvic tilt, contralateral pelvic rise, and hip joint external rotation, as compared with findings before surgery. When compared with healthy controls, patients with FAI demonstrated greater hip flexion as well as reduced pelvic forward rotation postoperatively. However, it remains unknown if these changes represent expected postoperative changes or persistent preoperative biomechanical alterations.

In general, the FAI group attenuated the magnitude of movement patterns at the hip and pelvis as compared with the control group during the step-down pivot-turn task. The differences in movement patterns between the FAI and control groups were most evident at the beginning and end of the task (Figure 2, A, C, D, F). At the beginning of the step-down pivot-turn cycle, the hip initially flexes, adducts, and externally rotates from initial contact through early limb loading (Figure 1B). The hip then moves toward extension, abduction, and external rotation from single-limb loading through completion of the task (Figure 1, C and D). Therefore, it is unlikely that purely symptomatic mechanical impingement contributes to attenuating these motions despite our finding of less hip joint flexion in patients with FAI. These results are consistent with a study by Savage et al,[33] who investigated walking biomechanics in patients with varying severities of cam-type FAI versus healthy controls. As in the current study, the authors used SPM analysis of time series waveforms and found a similar pattern of less hip flexion motion in patients with cam-type FAI as compared with controls at the beginning of the gait cycle.[33] Interestingly, they also found a similar pattern of attenuated hip external rotation and pelvis posterior rotation at the terminal stance phase just before toe-off, which is consistent with the current findings during the step-down pivot turn.[33]

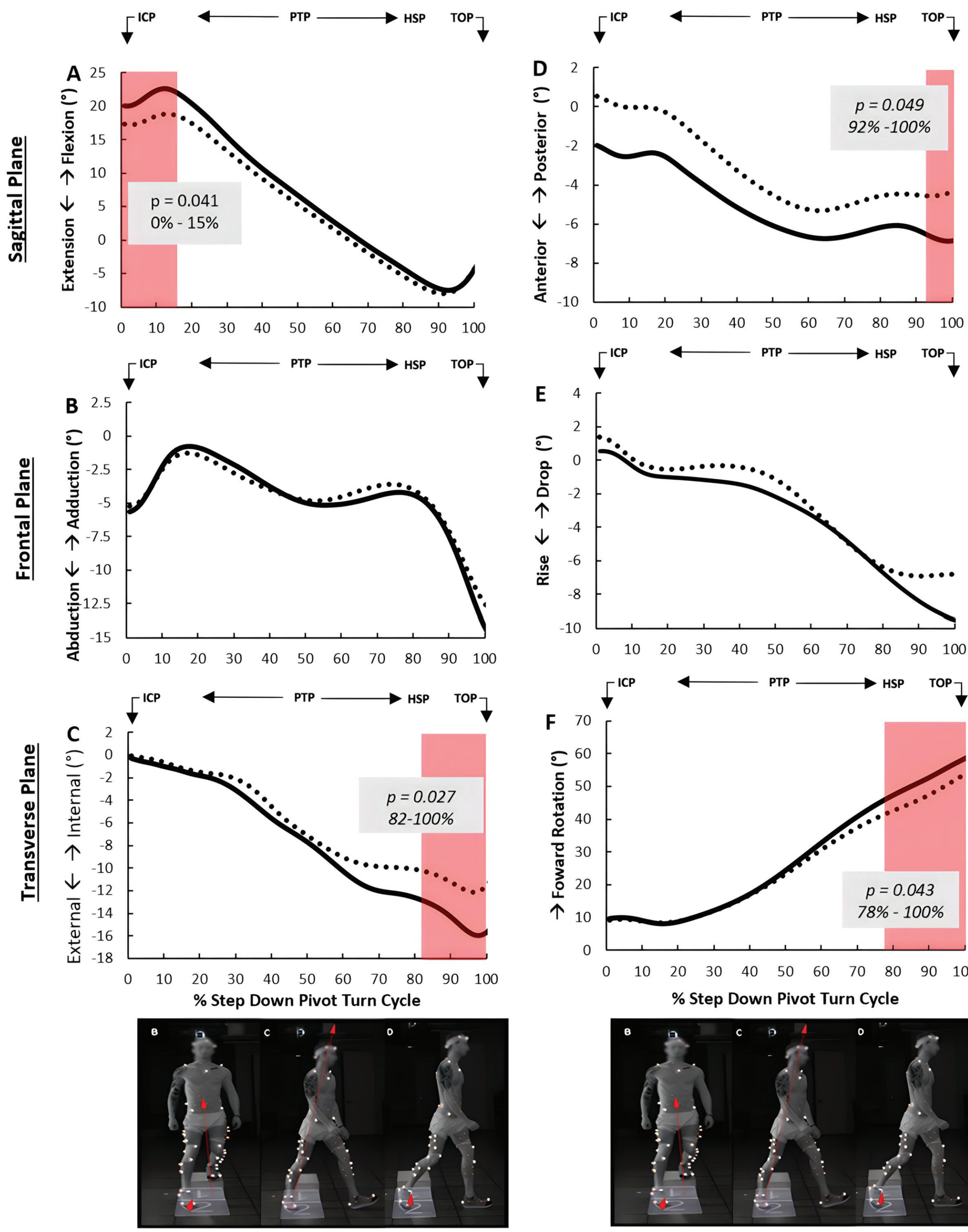

Figure 2. Comparison of (A-C) hip and (D-F) pelvis angle time series during a step-down pivot-turn task for each plane of motion: sagittal, frontal, and transverse. Patients with femoroacetabular impingement are represented by a black dotted line, and healthy controls are represented by a solid black line. Red-shaded regions indicate statistically significant difference between the groups ($P < .05$). HSP, heel-strike phase; ICP, initial contact phase; PTP, pivot-turn phase; TOP, toe-off phase.

Research comparing single discrete variables report mixed findings on biomechanical alterations during gait in patients with FAI as compared with controls. However, a number of these studies show attenuated hip motion during walking.[1,16] Given that a step-down pivot-turn task and gait task do not predispose patients to

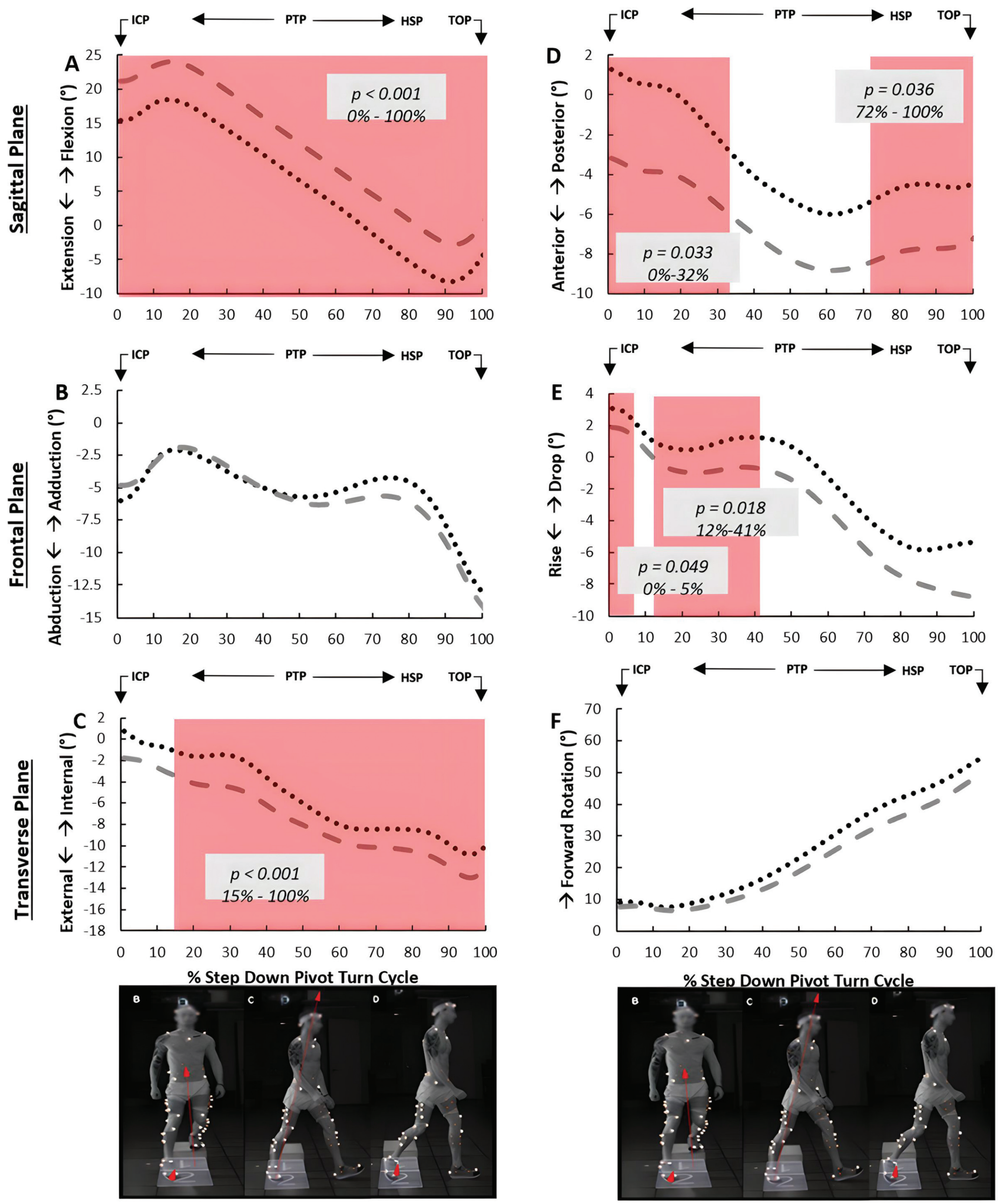

Figure 3. Comparison of (A-C) hip and (D-F) pelvis angle time series during a step-down pivot-turn task for each plane of motion: sagittal, frontal, and transverse. Time series for before surgery is represented by a dotted black line while after surgery is represented by a dashed gray line. Red-shaded regions indicate statistically significant difference between the groups ($P < .05$). HSP, heel-strike phase; ICP, initial contact phase; PTP, pivot-turn phase; TOP, toe-off phase.

symptomatic mechanical impingement at the hip, other factors related to pain, severity of joint damage, coexisting soft tissue injury, or altered neuromotor strategy could be contributors to the observed movement pattern alteration found in patients with FAI. Future research should compare movement patterns across different types of tasks in patients with FAI syndrome to determine if consistent alterations emerge regardless of the demands of the task. Additionally, this information could help reveal the role that movement analysis

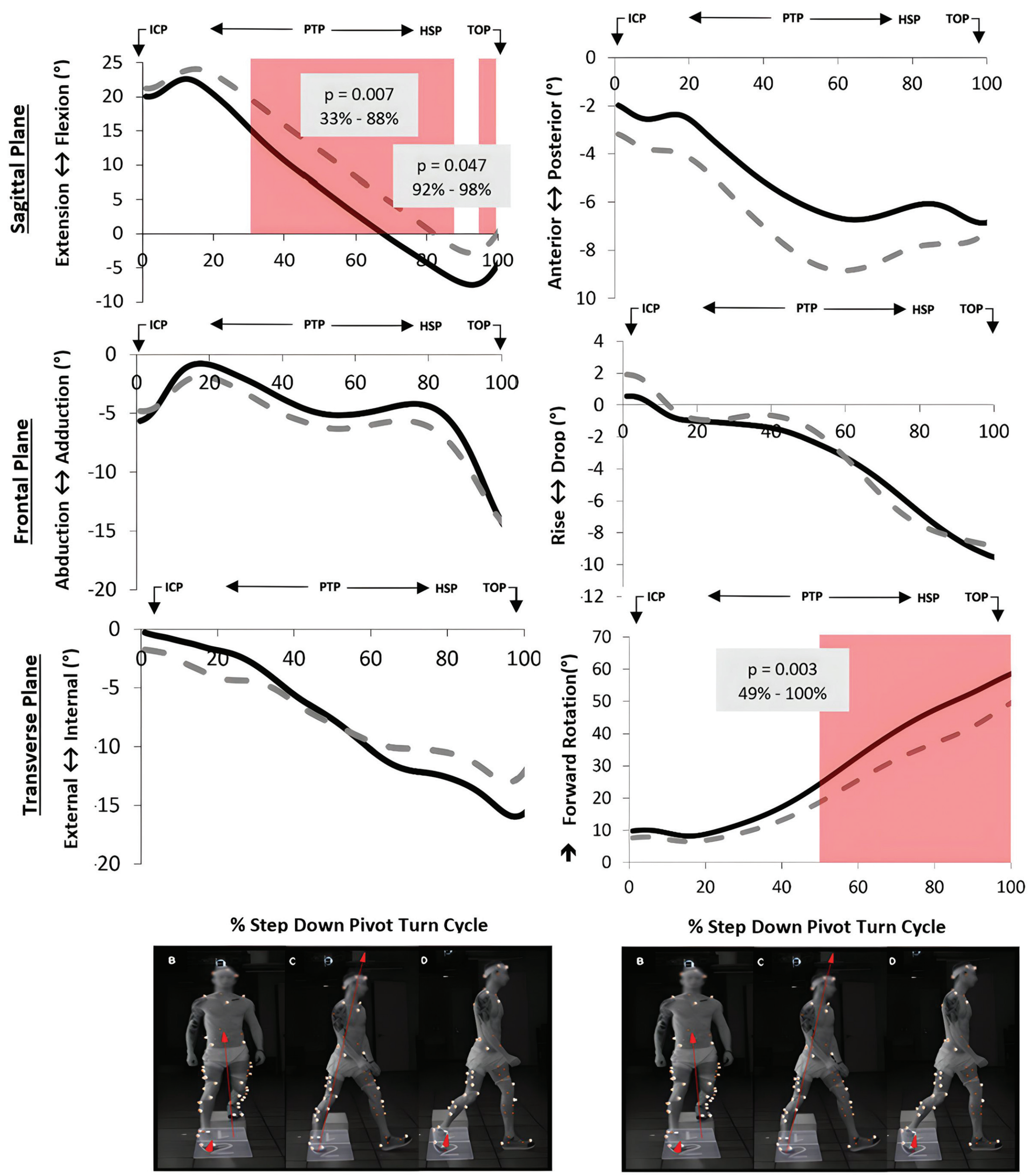

Figure 4. Comparison of (A-C) hip and (D-F) pelvis angle time series during a step-down pivot-turn task for each plane of motion: sagittal, frontal, and transverse. Time series for after surgery is represented by a dashed gray line while controls are represented by a solid black line. Red-shaded regions indicate statistically significant difference between the groups ($P < .05$). HSP, heel-strike phase; ICP, initial contact phase; PTP, pivot-turn phase; TOP, toe-off phase.

can play in diagnosis and treatment planning for cases of FAI.

Movement patterns at the hip and pelvis changed after hip arthroscopy as compared with presurgery, characterized by greater hip flexion, anterior pelvic tilt, external hip rotation, and contralateral pelvic rise. Additionally, when compared with controls, patients with FAI demonstrated increased hip flexion and reduced anterior pelvic forward rotation postoperatively. A number of factors could contribute to these changes, with one being that patients may undergo a neuromotor adjustment period after surgery. After hip arthroscopy, it is common for patients to exhibit less hip pain and experience increases in passive and active hip motion.[13-15] Therefore, although patients in the current study returned to essentially normal function, it is likely that a motor learning adjustment period was still in process on some level. Therefore, when patients with FAI syndrome performed the novel and deliberate step-down pivot-turn task, the movement patterns at the hip and pelvis may have reflected their adjustment to this new task and not their continued postoperative impairment. Additionally, those who underwent hip arthroscopy for FAI had significant improvements in patient-reported outcomes, which seem to support these changes being a normal postoperative adjustment and not functional impairment. However, differences were still noted in the hip sagittal plane and pelvis transverse plane after surgery when compared with controls, proposing that these adaptations represent alterations in motor control strategies facilitated by factors such as restricted soft tissue mobility, compensatory muscle activation, or pain avoidance.[7,16] A common practice in postoperative rehabilitation after hip arthroscopy is to limit hip external rotation and extension to minimize anterior-directed hip forces on repaired and healing tissue.[19] Therefore, perhaps the greater postoperative hip flexion noted in patients with FAI reflects these persistent avoidance deficits, combined with a lack of emphasis in restoring this motion during function, especially during the later phases of rehabilitation.[6,9,20] In addition, rehabilitation that emphasizes hip and pelvic strength and motor control to improve functional ROM in the transverse planes is typically initiated during later phases of rehabilitation protocols.[6,9,20] It is plausible that as hip function returns to normal, a lack of focus in these dynamic ranges resulted in persistent changes, as demonstrated versus controls. Furthermore, preoperative pain avoidance in patients with FAI may promote adapted movement patterns during activities. Although surgical intervention allows for removal of the pain-generating stimulus, it does not promote motor retraining. These subtle yet prolonged motor compensations and dysfunctional neuromuscular adaptions in response to pain may extend the postoperative course of rehabilitation, potentially explaining the persistent changes in ROM appreciated postoperatively as compared with controls. These deficits may also become more evident during tasks such as a step-down pivot turn, where the performance of the task is nuanced to emphasize a movement pattern deficit in a particular plane of motion.

Previous research suggests that patients may develop altered movement strategies to avoid pain during tasks that can reproduce symptomatic impingement.[7,22,23] Although the step-down pivot-turn task does not place the hip in a position of impingement, pain and irritation of associated hip joint tissues could still play a role in movement alterations during this task. Functionally, the iliofemoral ligament and acetabular labrum play an important role in limiting hip external rotation.[25] A substantial increase in labral tissue strain was found when the hip was externally rotated under axial load, which is functionally simulated during a step-down pivot-turn task.[25] Therefore, it is reasonable to speculate that a step-down pivot-turn task would place mechanical stress on the labrum and capsular ligaments during this task. As observed during squat-type tasks that were thought to compress injured tissues and as a way to avoid potentially painful positions of symptomatic impingement, perhaps people with FAI syndrome develop movement pattern alterations to reduce the tensile load through irritated or damaged tissues of the hip or focal chondral lesions. However, more research is needed to determine the function of the labrum during pivoting tasks to determine the cause of the movement alterations. A combination of in vitro and in silico investigations could help quantify actual tissue loads during impingement- and nonimpingement-related tasks.

Limitations

The findings of the current study should be considered within the context of current limitations. Not all control participants were screened for radiographic evidence of cam or pincer morphology or for the occurrence of acetabular labral tearing. This rationale was due to cost limitations, as MRI could not be performed as a screening tool for all controls in the current study, and we did not feel that exposing young healthy participants to ionizing radiation was ethically warranted for this study (in the case of radiographs). However, we randomly screened 10 controls for hip morphology abnormalities using MRI, and only 1 had asymptomatic cam morphology and none showed signs of acetabular dysplasia. In addition, the influence of chondral defects identified intraoperatively and their relationship with pre- and postoperative hip biomechanics was not included in the study. Furthermore, the diagnosis of FAI syndrome requires a triad consisting of hip symptoms, clinical signs, and imaging findings, which were used for screening of controls without FAI syndrome. While there were no differences in the proportion of female patients in the FAI and control groups, the present study did not control for sex. Though not all patients received physical therapy at the same facility, all were provided with the same postoperative rehabilitation protocol. While prior research has demonstrated that hip ROM is associated with acetabular version and femoral torsion,[17] bilateral pelvis and knee imaging to adequately assess acetabular morphology and femoral torsion, respectively, was not available in all patients.

CONCLUSION

Movement pattern differences between patients with FAI and controls during the nonimpingement-related step-down pivot-turn task were characterized by differences in the sagittal and transverse planes of the hip and pelvis. After hip arthroscopy, patients exhibited greater hip flexion and external rotation, as well as greater pelvic anterior tilt and pelvic rise, as compared with presurgery. When compared with controls, patients with FAI demonstrated increased hip flexion and reduced pelvic forward rotation postoperatively. These findings indicate that hip and pelvis biomechanics are altered even during tasks that do not reproduce the anterior impingement position.

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