Restricted Hip Rotation Is Correlated With an Increased Risk for Anterior Cruciate Ligament Injury

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Purpose: The primary purpose was to compare ipsilateral hip internal rotation (IR) in male and female athletes with or without an anterior cruciate ligament (ACL) tear. A secondary purpose was to compare radiographic markers of femoroacetabular impingement (FAI) in patients with or without an ACL tear. **Methods:** In this prospective case-control study, based on a power analysis, a convenience sample of 25 ACL-injured and 25 control patients matched by age and gender were examined over 14 months. The ACL injury group included preoperative patients 12-40 years old with an ACL rupture within the previous 3 months with no prior lower extremity injuries, ligamentous laxity, or arthralgias. Controls included patients presenting with an upper extremity complaint with no history of knee injury. In the outpatient clinic, hip axial rotation range of motion was measured with a goniometer on physical examination and hip radiographs were evaluated for morphologic variations consistent with FAI. Univariate analysis of variance was used to examine differences between groups. **Results:** Each group had 13 males and 12 females, average ages of 22.8 ± 7.2 years (ACL group) versus 24.5 ± 7.9 years (controls; $P = .439$). The average sum of hip rotation (internal plus external) in patients with an ACL tear was $60.3 \pm 12.4°$ compared with $72.6 \pm 17.2°$ in controls ($P = .006$). ACL-injured patients had decreased hip IR compared with controls, with respective mean measurements of $23.4 \pm 7.6°$ versus $30.4 \pm 10.4°$ ($P = .009$). For every 10° increase in hip IR, the odds of having an ACL tear decreased by a factor of 0.419 ($P = .015$). **Conclusions:** Risk of ACL injury is associated with restricted hip IR, and as hip IR increases, the odds of having an ACL tear decreases. In addition, ACL injury is associated with FAI in a generalized population of male and female athletes, although causality cannot be determined and most ACL-injured patients do not exhibit hip complaints. **Level of Evidence:** Level II, prognostic, prospective cohort study.

Injuries to the anterior cruciate ligament (ACL) continue to occur at significant rates.[1,2] Given that injuries to the ACL pose public health and financial burdens because of their short- and long-term consequences,[3] insights are needed to better prevent ACL injuries. Previous ACL injury remains one of the leading risk factors for a subsequent ACL injury, suggesting that predisposing risk factors may remain a potential source of future morbidity.[4]

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Many factors contributing to ACL injury risk have been investigated,[5] and attention has most often focused on the variable anatomy and secondary impact on kinematics of the knee joint.[6-9] In the continued search for what predisposes certain athletes to ACL injury, the hip joint, as part of a complex kinetic chain with compensatory function, is a potential contributory factor. Abnormalities in proximal femoral and/or acetabular anatomy are known to result in secondary restriction in hip range of motion (ROM).[10] Restricted passive hip rotation ROM has been correlated with ACL ruptures and reruptures caused by noncontact trauma in soccer athletes.[11-13] In a population of 13- to 17-year-old student athletes, limited hip rotation ROM was associated with increased risk of noncontact ACL injury.[14] Similarly, players at the 2012 National Football League Combine with a restricted range of internal rotation (IR) at the hip were more likely to have sustained an ACL injury that required surgical reconstruction.[15] When comparing ACL-injured individuals with a control group with non-ACL knee injuries for evidence of cam-type femoroacetabular impingement (FAI) on radiographic measures, the ACL-injured patients had a mean α angle of 84° as compared with 59° in the control population.[16]

Variable proximal femoral and acetabular morphology is extremely common in the general population,[17,18] and the secondary impact of this variation on hip ROM and the kinetic chain is significant. Evidence of FAI on imaging is present in 6% to 37% of asymptomatic individuals.[17-22] Moreover, noncontact cutting and pivoting injuries typically include a forceful valgus and rotational component, and occur most commonly with the knee near full extension with an associated plant-and-cut movement or a single-legged jump stop landing.[23] These noncontact mechanisms are responsible for as many as 80% of ACL tears in athletes,[24] highlighting the potential influence that restricted hip rotation may have on ACL injury risk.

During biomechanical simulation of a jump landing, tibial IR and knee valgus moment can be generated, leading to increased ACL strain.[25,26] Restriction of IR at the hip may require athletes to generate greater compensatory IR of the tibia to successfully complete athletic tasks.[27] Also, limiting the range of internal femoral rotation during repetitive simulated jump landings increases the risk of an ACL fatigue failure in comparison with free hip rotation in a cadaveric model.[28] In silico models also support this association by showing increased peak strain of the anteromedial bundle of the ACL with decreased maximal IR.[15]

Existing clinical studies are limited by various biases, including retrospective designs, lack of control groups in some studies, and select patient populations.[11-16] The primary purpose of this study was to compare ipsilateral hip IR in patients with or without an ACL tear in a population of male and female athletes. A secondary purpose was to compare radiographic markers of FAI in patients with or without an ACL tear. We hypothesized that patients presenting with an acute ACL injury would be more likely to have decreased hip rotation ROM on physical examination when compared with a control group. It was also hypothesized that patients presenting with an ACL injury would be more likely to have radiographic evidence of FAI when compared with a control group.

Methods

This study was approved by our Institutional Review Board. All patients provided written informed consent before participation in the study, including patient assent and parental consent for patients less than 18 years of age. From March 2014 through May 2015 a convenience sample of nonconsecutive patients ($n = 25$) presenting to an orthopaedic clinic and identified as having an acute ACL tear on physical examination and magnetic resonance images were invited to participate in this prospective case-control study, and during the same time frame were prospectively matched by age and gender to a control group ($n = 25$) presenting with an upper extremity musculoskeletal complaint and no history of knee injury or surgical treatment. Inclusion criteria for the ACL injury group were preoperative patients between 12 and 40 years old with a diagnosis of a noncontact ACL rupture less than 3 months previously. The control group included patients matched by age and gender to the ACL injury group presenting to a clinic with an upper extremity musculoskeletal complaint. After an ACL-injured patient was enrolled in the study, a control subject who was within ±3 years of the ACL-injured patient age was enrolled. Exclusion criteria for the ACL and control groups were assessed with a preparticipation questionnaire and interview with research personnel completed by the patient, and family members in cases of minors. Patients were excluded from the study if they were found to have any of the following: history of prior lower extremity surgery or fracture, including history of hip injury, hip dysplasia, or FAI, or any known hip abnormality, history of joint or connective tissue laxity, history of rheumatoid arthritis or polyarthralgias, and the presence of clinical discrepancies of lower limb length (Fig 1). Baseline demographic information, including age and gender, was recorded, and data collected from the history included the side of the ACL injury, mechanism of injury, and presence of prior hip symptoms. Preinjury Tegner scores were self-reported. All participants had the history and physical examination performed by 1 of 2 orthopaedic surgery sports medicine fellows in training, and because of the clinical availability of these fellows, patients were enrolled nonconsecutively, and only during clinics in which the fellows were present. One orthopaedic surgeon performed hip ROM measurements on the first 12 patients enrolled, followed by the second orthopaedic surgeon who performed measurements on the final 38 patients enrolled. Intraclass correlation coefficients, including interobserver and intraobserver reliability indices, were later performed to assess reliability of hip ROM measurements. All ACL-injured and control subjects were enrolled and completed participation in this study during the same time period, which was between March 2014 and May 2015. Periodic comparisons between ACL and control groups were made throughout the study period with respect to age and gender to match these variables.

Hip ROM was assessed in bilateral lower extremities in all participants, including a measure of terminal hip flexion, IR in 90° of hip flexion, and external rotation (ER) in 90° of hip flexion while stabilizing the pelvis to engage the femoral head-neck junction with the acetabular rim. The contralateral hip was maintained in full extension during all measures. These measurements were performed in triplicate with a universal

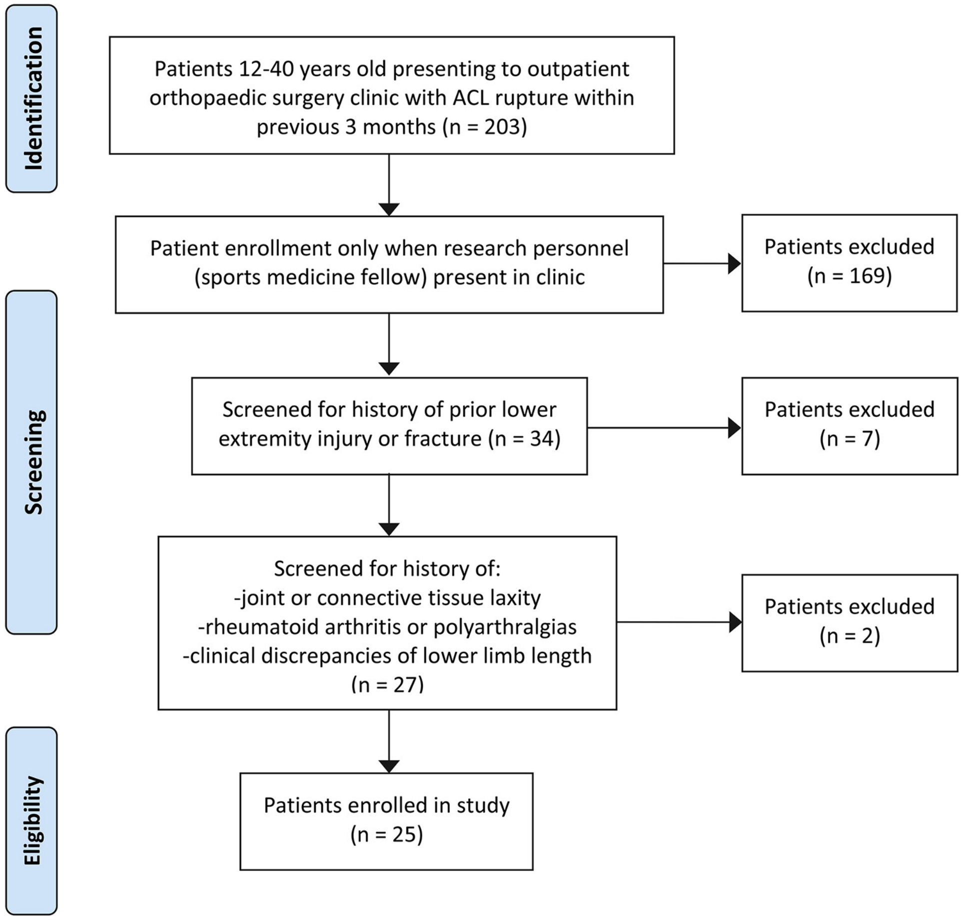

Fig 1. Screening of patients with injuries of the anterior cruciate ligament (ACL).

goniometer and mean values were calculated. High intraclass correlations for hip ROM measurements using this technique have been shown.[29] The ipsilateral hip on which the ACL injury occurred was defined as the affected side, with the contralateral side considered the unaffected side; for the control group, the ipsilateral hip was defined as the same side as the upper extremity injury. Intraclass correlation coefficients were calculated to assess the interobserver and intraobserver reliabilities of these physical examination hip ROM measurements. Hip ROM between groups, including hip flexion, IR, ER, and summed rotation (IR + ER), were compared, and percentage of patients with IR $< 30°$ and combined IR + ER $< 75°$ were assessed. In addition, the odds ratios for ACL tear with increasing intervals of 10° of IR were calculated.

Radiographic analysis consisted of standardized radiographs, including weight-bearing anteroposterior pelvis and Dunn 45° and Dunn 90° extended neck lateral images. On the basis of published recommendations for radiographic evaluation of FAI, the following were measured: lateral center edge angle, Tönnis angle, maximum α angle, femoral head-neck offset (HNO), and other markers of FAI, including crossover sign, posterior wall sign, ischial spine sign, and coxa profunda, on the affected side.[30] All radiographic measurements were performed using digital software (Imagecast PACS 3.6.134.0, GE Healthcare, Barrington, IL) by 1 of 2 orthopaedic surgery sports medicine fellows in training. Research team members were not blinded to ACL injury versus control groups at the time of hip ROM measurements or radiographic measurements. The means for lateral center edge angle, Tönnis angle, maximum α angle, and HNO were calculated for each group, and the percentages of patients in each group with radiographic markers of FAI were recorded.

Statistical Analysis

An a priori analysis was performed, and our team of investigators estimated that a clinically significant difference between groups for hip rotation would be 10° with a standard deviation of 5°. To obtain a power of 0.80 or higher, we would need a minimum of 17 patients in the ACL-injured group and 17 patients in the control group. Clinical data from Excel (Microsoft, Redmond, WA) spreadsheets were imported into SPSS version 22.0 statistical software (IBM, Armonk, NY)

Table 1. Demographic Characteristics of Subjects

	ACL Tear (n = 25)	Control (n = 25)	*P* Value
Age, yr, mean ± SD	22.8 ± 7.24	24.45 ± 7.90	.439
Gender, male/female, n	13/12	13/12	
Injury side, left:right, n	19:6	12:13	.04
Days from injury, mean ± SD	30.8 ± 23.8		

ACL, anterior cruciate ligament.

for statistical analysis. For all analyses, $P < .05$ was defined as significant. Analyses included descriptive statistics to examine measures of central tendency, which included mean and standard deviation. Inferential statistics used to examine differences between baseline characteristics were χ^2 and Student's *t*-test. Univariate analysis of variance was used to examine differences between groups for ROM and radiologic measurements. Within-group differences for ROM measurements were assessed by Student's *t*-test. Logistic regression was used to examine ROM measurements as predictors of injury. After data collection, to dichotomize patients from the ACL injury and control groups based on hip ROM, specific values for IR and IR + ER were chosen within the closest 5° to define what percentage from each group were above and below these chosen threshold measurements. Intraclass correlations were calculated for interobserver and intraobserver reliability of hip ROM measurements.

Results

A total of 25 ACL-injured and 25 control patients participated in the study, with 13 male and 12 female patients in both groups. The mean age was similar for both groups. The ACL-injured group was examined an average of 30.8 days after injury. In the ACL-injured group, a greater proportion of injuries occurred on the left side as compared with the side of upper extremity injury in the control group ($P = .04$). Preinjury Tegner scores were significantly higher in the ACL-injured group than in the control group, with self-reported scores of 7.68 and 6.72 ($P = .024$), respectively. One ACL-injured and zero control patients reported a history of prior hip pain. Basketball and soccer were the most common ACL injury mechanisms, whereas the control group consisted of patients with a variety of upper extremity injuries, most commonly traumatic shoulder instability and biceps tendinopathy. The characteristics of the participants are summarized in Tables 1 and 2.

There were significant differences between the groups for IR and summed IR + ER ROM. IR in the ACL-injured group averaged 23.4 ± 7.6° compared with 30.4 ± 10.4° ($P = .009$) in the control group. Summed IR + ER was 60.3 ± 12.4° versus 72.6 ± 17.2° ($P = .006$) in the ACL-injured and control groups, respectively. Hip ROM measurements and differences between groups in the unaffected side closely paralleled those of the affected side (Table 3).

Figure 2 reports the percentage of patients from each group who were found to have hip IR ≤ 30° and IR + ER ≤ 75° on the affected side. Eighty-eight percent of ACL-injured patients had IR ≤ 30° compared with 48% of control patients ($P < .009$). Summed IR + ER ≤ 75° was found in 92% versus 52% ($P = .006$) of ACL-injured and control patients, respectively.

Logistic regression analysis of ROM shows that for every 10° increase in IR in the affected hip, the odds of having an ACL tear decrease by a multiplicative factor of 0.419 (Table 4).

When males and females were analyzed separately, significant differences were found in both groups for IR + ER, whereas the female participants showed greater differences in IR (Table 5).

When male and female patients were assessed together, radiographic analysis revealed no significant differences between groups with respect to markers of cam-type morphology or hip dysplasia; however,

Table 2. Baseline Clinical Characteristics of Subjects

	ACL Tear (n = 25)	Control (n = 25)	*P* Value
Tegner score, mean ± SD	7.68 ± 1.41	6.72 ± 1.49	.024
Prior hip pain, n	1/25	0/25	NS
Injury mechanism	Basketball, 36%	Traumatic shoulder instability, 44%	
	Soccer, 32%	Biceps tendinopathy, 24%	
	Football, 4%	Scapular dyskinesia, 12%	
	Rugby, 4%	Rotator cuff tendinopathy, 4%	
	Volleyball, 4%	Acromioclavicular joint strain, 4%	
	Lacrosse, 4%	Capitellar osteochondritis dissecans lesion, 4%	
	Downhill skiing, 4%	Elbow ulnar collateral ligament injury, 4%	
	Mixed martial arts, 4%	Clavicle fracture, 4%	
	Track, 4%		
	Jogging, 4%		

ACL, anterior cruciate ligament; NS, not significant.

Table 3. Comparison of Hip Range of Motion Between Groups

	ACL Tear (n = 25), Mean ± SD	Control (n = 25), Mean ± SD	*P* Value	95% Confidence Interval	
				Lower	Upper
Flexion					
Affected side	106.9 ± 7.6°	103.7 ± 6.2°	.104	−7.197	0.691
Unaffected side	108.7 ± 7.7°	104.4 ± 5.8°	.030	−16.051	0.211
Internal rotation					
Affected side	23.4 ± 7.6°	30.4 ± 10.4°	.009	1.829	12.198
Unaffected side	24.5 ± 6.5°	31.8 ± 9.9°	.003	2.543	12.124
External rotation					
Affected side	36.9 ± 8.4°	42.2 ± 10.7°	.057	−0.165	10.805
Unaffected side	37.5 ± 10.2°	43.0 ± 11.3°	.076	−0.595	11.635
Internal rotation + external rotation					
Affected side	60.3 ± 12.4°	72.6 ± 17.2°	.006	3.797	20.869
Unaffected side	62.0 ± 13.9°	74.9 ± 17.2°	.006	3.941	21.766

ACL, anterior cruciate ligament; SD, standard deviation.

significant differences were noted in markers of pincer-type morphology. In particular, ACL-injured patients showed significantly greater incidences of a positive posterior wall sign and a positive ischial spine sign (Table 6).

Intraclass correlation assessments for hip measurements, including 7 patients measured for interobserver reliability and 8 patients measured for intraobserver reliability, using an absolute agreement definition showed agreement across raters of 0.90 ($P < .001$) for all measures.

Table 7 describes the significant differences that were found with respect to cam-type morphology when male and female patients were analyzed separately. In males, the average α angle on Dunn 90° radiographs was 53.9 ± 9.9° and 50.8 ± 8.8° ($P = .046$) in the ACL-injured and control groups, respectively. In females, the average α angle on anteroposterior radiographs was 45.0 ± 5.8° and 41.0 ± 2.8° ($P = .046$) in the ACL-injured and control groups, respectively.

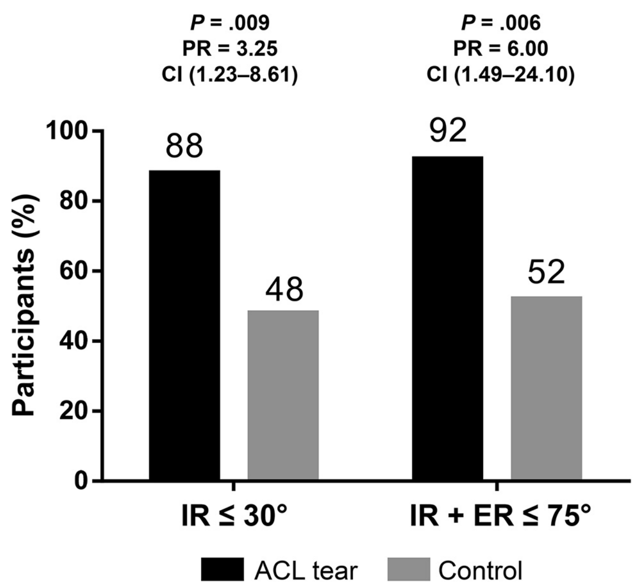

Fig 2. Incidence of individuals with hip range of motion below selected cutoff values. (ACL, anterior cruciate ligament; CI, confidence interval; ER, external rotation, IR, internal rotation, PR, prevalence ratio.)

Discussion

The results of this study show a correlation between restricted hip rotation ROM and an increased risk of ACL injury, along with a relation between cam and pincer FAI morphology and ACL injury. The current study suggests that restriction in hip axial rotation, especially IR and summed IR + ER, is associated with an increased risk of ACL rupture in a generalized population of male and female athletes. In this study population, participants who had sustained an ACL tear had significantly greater restriction in hip ROM compared with matched controls. Only one of these patients, however, had symptoms in the groin or hip, suggesting this asymptomatic finding in most may not be recognized without a low threshold for consideration by the treating clinician. Reductions in hip rotation may induce compensatory stresses on the knee that predispose patients to a greater risk of ACL injury.[15,27,28]

The morphologic variations that are associated with dynamic hip impingement and associated loss of motion include femoral retroversion, cam-type morphology, loss of HNO, and acetabular retroversion.[31] These morphologic variations are common in athletes, possibly due to the repetitive high load, and rotational forces on the physes, leading to developmental growth alterations and subsequent nonphysiologic remodeling of the femoral head.[31] Prior studies have shown a correlation between cam-type FAI and ACL injury; the data from this study showed a weaker correlation between these variables.[16] Also, evidence of a higher prevalence of pincer-type FAI was found in the ACL group, with significantly higher

Table 4. Logistic Regression of Range of Motion (ROM) Measures as a Predictor of Anterior Cruciate Ligament (ACL) Injury Group by Side for Every 10° Increase in ROM

	Odds Ratio	95% Confidence Interval	*P* Value
Internal rotation			
Affected side	−0.419	0.207, 0.847	.015
Unaffected side	−0.343	0.156, 0.755	.008
Internal rotation + external rotation			
Affected side	−0.570	0.372, 0.875	.010
Unaffected side	−0.586	0.389, 0.884	.011

prevalence of markers of acetabular retroversion, as measured by the posterior wall and ischial spine signs.

The important role of a tibial IR moment on ACL injury has been well documented.[25,26] Further studies have shown the impact of decreased femoral IR in increasing ACL strain as well as the risk of ACL fatigue failure.[15,27,28] A clinical correlation between decreased hip ER as well as combined IR + ER and increased ACL injury risk has also been reported, whereas current biomechanical evidence to support this paradigm is lacking.[11,13,14] In this study, hip rotation ROM data, both IR and IR + ER, were relatively similar between male and female patients, yet there is a known higher rate of ACL tears in females. Hip rotation ROM alone clearly does not explain these gender differences and the study of other etiologic factors for ACL tears should be continued.

The impact of FAI and limited hip rotation on ACL injury risk has implications for improvement of jump and pivot-landing techniques for ACL injury prevention in sport.[15] Prior studies have shown the positive impacts of ACL injury prevention programs focusing on neuromuscular training, functional motor control exercises, isolated hip strengthening, and hip stretching in soccer players and military personnel.[32-34] The findings of this study are preliminary, which suggest that further prospective and blinded studies are needed in patient populations that are more homogeneous with respect to gender, sport, and activity level. If the current findings can be shown to be consistent and relevant, consideration may be given to operative hip intervention to improve femoral axial rotation in select patients, in addition to these exercise and therapy approaches. Potentially, those with symptomatic FAI and recurrent ACL failure in a revision ACL reconstruction setting may mitigate future ACL injury risk by treating the symptomatic hip disease. There is strong evidence to show improvement in hip kinematics and ROM, particularly IR, in FAI-related disease of the hip after arthroscopic decompression.[35-37]

The findings of this study have clinical significance for athletes who wish to engage in cutting and pivoting activities. This study prospectively showed a correlation between restricted hip ROM, especially IR and IR + ER, and an increased risk of ACL injury in a generalized population of male and female athletes. Biomechanical studies have shown the impact that restricted hip IR has on increasing ACL strain through a compensatory increase in tibial axial IR.[15,27,28] Identifying athletes with restricted hip rotation, especially IR, should generate appropriate counseling to these athletes who may be at an increased risk for ACL injury. Focused therapy programs and appropriate training modifications may improve hip function and help prevent ACL injuries. Also, assessment of hip rotation should be part

Table 5. Comparison of Hip Range of Motion Between Groups by Gender

	Males				
				95% Confidence Interval	
	ACL Tear Males (n = 13), Mean ± SD	Control Males (n = 13), Mean ± SD	*P* Value	Lower	Upper
Mean internal rotation					
Affected side	23.4 ± 7.6°	25.1 ± 7.9°	.088	−0.788	10.634
Unaffected side	24.5 ± 6.5°	27.0 ± 7.7°	.109	−0.954	8.954
Mean internal rotation + external rotation					
Affected side	60.3 ± 12.4°	65.3 ± 15.4°	.051	−0.064	18.628
Unaffected side	62.0 ± 13.9°	67.7 ± 15.2°	.042	0.396	19.501
	Females				
				95% Confidence Interval	
	ACL Tear Females (n = 12), Mean ± SD	Control Females (n = 12), Mean ± SD	*P* Value	Lower	Upper
Mean internal rotation					
Affected side	24.1 ± 8.2°	30.4 ± 10.4°	.003	3.417	15.138
Unaffected side	25.0 ± 7.0°	31.8 ± 9.9°	.001	5.724	16.165
Mean internal rotation + external rotation					
Affected side	61.7 ± 13.2°	72.6 ± 17.2°	.001	7.903	23.375
Unaffected side	63.5 ± 14.5°	74.9 ± 17.2°	.002	6.668	25.332

ACL, anterior cruciate ligament; SD, standard deviation.

Table 6. Comparison of Radiographic Markers Between Groups

	ACL Tear (n = 25), Mean ± SD	Control (n = 25), Mean ± SD	*P* Value	95% Confidence Interval Lower	95% Confidence Interval Upper
Dysplasia					
LCEA, °	27.6 ± 5.9	29.9 ± 4.9	.891	−0.770	5.410
Tönnis angle, °	6.3 ± 3.5	5.4 ± 3.8	.626	−3.001	1.161
Cam					
AP α, °	48.7 ± 8.3	45.2 ± 7.7	.409	−8.086	1.046
AP HNO, mm	8.2 ± 1.9	8.6 ± 1.3	.106	−0.4907	1.347
Dunn 45° α angle, °	56.2 ± 9.7	52.8 ± 8.6	.383	−8.649	1.769
Dunn 45° HNO, mm	7.5 ± 1.9	8.2 ± 1.6	.613	−0.308	1.724
Dunn 90° α angle, °	53.9 ± 9.9	49.2 ± 8.5	.167	−9.924	0.564
Dunn 90° HNO, mm	8.5 ± 2.0	8.9 ± 1.7	.439	−0.653	1.477
Pincer					
Crossover sign +	28%	12%	.164		
Post wall sign +	36%	4%	.004		
Ischial spine sign +	24%	4%	.042		
Coxa profunda +	56%	40%	.267		

NOTE. Statistical analyses for dysplasia and cam markers performed with Student's *t*-test. Pincer markers assessed with χ^2 analysis.
ACL, anterior cruciate ligament; AP, anteroposterior; HNO, femoral head-neck offset; LCEA, lateral center edge angle; SD, standard deviation.

of the evaluation of a patient who has suffered a recurrent ACL tear, and be an additional reason for treatment in a patient with associated symptomatic hip impingement. Detailing this association may lead to better understanding of ACL injury risk, more appropriate interventions for ACL injury prevention, and improved understanding of ACL reconstruction failure. However, these results do not provide causation, nor do they advocate for the prophylactic surgical correction of restricted hip rotation as a way of reducing ACL injury risk.

Limitations

Several limitations of the present study are acknowledged. First, a small number of participants were enrolled; however, the study was sufficiently powered to identify meaningful differences, and enrolling patients to undergo otherwise unnecessary pelvic and hip radiographs is difficult to justify and accomplish. Further, more pronounced differences for hip IR and combined IR + ER were noted in females, with differences between groups more closely approaching the predetermined clinically significant difference of 10° in the female group; future studies with increased numbers of participants may help to better elucidate possible gender differences. Before this study, a hip ROM difference of 10° was determined to be both the minimum clinically important difference and the minimum detectable change, based on the American Medical Association's recommendations as well as prior studies assessing hip ROM in healthy adults and professional baseball players.[38-42] Second, although all participants were part of a generalized group of athletic patients, their preinjury activity levels, as measured by the Tegner score, differed between groups, with the ACL group reporting a higher level of activity. It is possible that an element of recall bias could have impacted patient self-reported Tegner scores, which were given after the injury. This study matched ACL-injured and control patients by age and gender; future studies should attempt to match groups with respect to sport and activity level as well. Third, research team members were not blinded to whether the study patient was part of the ACL-injured or control group during hip ROM measurements or during radiographic measurements; however, strong intraclass correlations were found for ROM measurements. Although future study designs could blind researchers to the study group during radiographic measurements, it would likely be difficult to blind researchers to ACL injury during physical examination measurements given the possibility that it may be possible to recognize a recently injured knee during examination of the hip. This study was limited by the fact that 1 of 2 orthopaedic surgery sports medicine fellows conducted all of the hip examinations for this study, and patient

Table 7. Summary of Significant Findings in Comparison of Radiographic Markers Between Groups by Gender

	ACL Tear	Control	*P* Value	95% Confidence Interval Lower	95% Confidence Interval Upper
Male Dunn 90° α angle, °	53.9 ± 9.9	50.8 ± 8.8	.046	−14.640	0.129
Female AP α angle, °	45.0 ± 5.8	41.0 ± 2.8	.046	−7.750	0.084

ACL, anterior cruciate ligament; AP, anteroposterior.

enrollment depended on the availability of 1 of these 2 fellows at the time of the patient's clinical visit, thus precluding consecutive patient enrollment. In addition, during hip ROM measurements, attempts were made to stabilize the pelvis with the contralateral hip in full extension, although it is likely that as the ipsilateral hip was brought into further flexion, some degree of pelvic tilt posteriorly occurred rather than hip flexion, which may have altered some of the recorded ROM measurements, particularly hip flexion.

Further shortcomings include the lack of an assessment of femoral version, as multiplanar imaging studies of the hip and knee were not obtained. Femoral version has been correlated with both hip ROM and ACL injury risk.[31,43] Although hip ROM measurements were made on ACL-injured patients an average of 30.8 ± 23.8 days after injury, no significant differences were noted between the ipsilateral and contralateral hips, suggesting that no stiffness or injury-related changes in hip ROM were found; moreover, with respect to hip IR, the end point of hip ROM was assessed by femoral head-neck junction contact with the acetabular rim in the clinical judgment of the examiner. Also, although there were no side-to-side differences in hip ROM measurements in the statistical analysis for this study, there were more left hips measured as the "affected" side in the ACL group versus the control group. Control patients in this study were matched to the ACL group by age and gender, and rather than choosing the ipsilateral hip to the injured upper extremity as the "affected" hip in the control group, matching hip laterality to the ACL-injured group may have optimized this analysis. Also, although our intraclass correlation analysis was strong, it was limited to 7 of 50 patients being measured by both research team members for the interobserver reliability, and 8 of 50 patients for the intraobserver reliability. It is possible that if a greater number of repeat hip ROM measurements had been performed by research team personnel, the results of the intraclass correlation analysis could have differed from those obtained in this study based on a limited number of repeat measurements. Ideally, patients could be examined before injury and followed longitudinally in a prospective fashion; this study enrolled patients after ACL or upper extremity injury, but all measurements and data were gathered in a prospective fashion. Perhaps a more optimal control group would have been uninjured healthy control patients rather than those with an upper extremity injury so as to limit any potential correlations with loss of hip ROM and shoulder or elbow injuries, particularly in throwers. In addition, although patients were screened and excluded for joint or connective tissue laxity, screening was based primarily on intake interview, and a more systematic screening could have included a physical examination assessment for this as well. Lastly, although this study provides evidence to support an association between restricted hip rotation and an increased risk for ACL injury, causation between these factors cannot be established.

Conclusions

Risk of ACL injury is associated with restricted hip IR, and as hip IR increases, the odds of having an ACL tear decreases. In addition, ACL injury is associated with FAI in a generalized population of male and female athletes, although causality cannot be determined and most ACL-injured patients do not exhibit hip complaints.

References

1. Joseph AM, Collins CL, Henke NM, Yard EE, Fields SK, Comstock RD. A multisport epidemiologic comparison of anterior cruciate ligament injuries in high school athletics. *J Athl Train* 2013;48:810-817.
2. McCarthy MM, Voos JE, Nguyen JT, Callahan L, Hannafin JA. Injury profile in elite female basketball athletes at the Women's National Basketball Association combine. *Am J Sports Med* 2013;41:645-651.
3. Riordan EA, Frobell RB, Roemer FW, Hunter DJ. The health and structural consequences of acute knee injuries involving rupture of the anterior cruciate ligament. *Rheum Dis Clin North Am* 2013;39:107-122.
4. Orchard J, Seward H, McGivern J, Hood S. Intrinsic and extrinsic risk factors for anterior cruciate ligament injury in Australian footballers. *Am J Sports Med* 2001;29:196-200.
5. Shultz SJ, Schmitz RJ, Benjaminse A, Chaudhari AM, Collins M, Padua DA. ACL Research Retreat VI: An update on ACL injury risk and prevention. *J Athl Train* 2012;47:591-603.
6. Kristianslund E, Krosshaug T. Comparison of drop jumps and sport-specific sidestep cutting: Implications for anterior cruciate ligament injury risk screening. *Am J Sports Med* 2013;41:684-688.
7. Shin CS, Chaudhari AM, Andriacchi TP. Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Med Sci Sports Exerc* 2011;43:1484-1491.
8. Torry MR, Shelburne KB, Myers C, et al. High knee valgus in female subjects does not yield higher knee translations during drop landings: A biplane fluoroscopic study. *J Orthop Res* 2013;31:257-267.
9. Wordeman SC, Quatman CE, Kaeding CC, Hewett TE. In vivo evidence for tibial plateau slope as a risk factor for anterior cruciate ligament injury: A systematic review and meta-analysis. *Am J Sports Med* 2012;40:1673-1681.
10. Audenaert EA, Peeters I, Vigneron L, Baelde N, Pattyn C. Hip morphological characteristics and range of internal rotation in femoroacetabular impingement. *Am J Sports Med* 2012;40:1329-1336.
11. Ellera Gomes JL, Palma HM, Ruthner R. Influence of hip restriction on noncontact ACL rerupture. *Knee Surg Sports Traumatol Arthrosc* 2014;22:188-191.
12. Gomes JL, de Castro JV, Becker R. Decreased hip range of motion and noncontact injuries of the anterior cruciate ligament. *Arthroscopy* 2008;24:1034-1037.

13. Lopes OV Jr, Gomes JL, de Freitas Spinelli L. Range of motion and radiographic analysis of the hip in patients with contact and non-contact anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc* 2016;24:2868-2873.
14. Tainaka K, Takizawa T, Kobayashi H, Umimura M. Limited hip rotation and non-contact anterior cruciate ligament injury: A case-control study. *Knee* 2014;21:86-90.
15. Bedi A, Warren RF, Wojtys EM, et al. Restriction in hip internal rotation is associated with an increased risk of ACL injury. *Knee Surg Sports Traumatol Arthrosc* 2016;24:2024-2031.
16. Philippon M, Dewing C, Briggs K, Steadman JR. Decreased femoral head-neck offset: A possible risk factor for ACL injury. *Knee Surg Sports Traumatol Arthrosc* 2012;20:2585-2589.
17. Hack K, Di Primio G, Rakhra K, Beaule PE. Prevalence of cam-type femoroacetabular impingement morphology in asymptomatic volunteers. *J Bone Joint Surg Am* 2010;92:2436-2444.
18. Jung KA, Restrepo C, Hellman M, AbdelSalam H, Morrison W, Parvizi J. The prevalence of cam-type femoroacetabular deformity in asymptomatic adults. *J Bone Joint Surg Br* 2011;93:1303-1307.
19. Frank JM, Harris JD, Erickson BJ, et al. Prevalence of femoroacetabular impingement imaging findings in asymptomatic volunteers: A systematic review. *Arthroscopy* 2015;31:1199-1204.
20. Laborie LB, Lehmann TG, Engesaeter IO, Eastwood DM, Engesaeter LB, Rosendahl K. Prevalence of radiographic findings thought to be associated with femoroacetabular impingement in a population-based cohort of 2081 healthy young adults. *Radiology* 2011;260:494-502.
21. Monazzam S, Bomar JD, Dwek JR, Hosalkar HS, Pennock AT. Development and prevalence of femoroacetabular impingement-associated morphology in a paediatric and adolescent population: A CT study of 225 patients. *Bone Joint J* 2013;95-B:598-604.
22. Reichenbach S, Juni P, Werlen S, et al. Prevalence of cam-type deformity on hip magnetic resonance imaging in young males: A cross-sectional study. *Arthritis Care Res (Hoboken)* 2010;62:1319-1327.
23. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *Am J Sports Med* 2004;32:1002-1012.
24. Quatman CE, Kiapour AM, Demetropoulos CK, et al. Preferential loading of the ACL compared with the MCL during landing: A novel in sim approach yields the multiplanar mechanism of dynamic valgus during ACL injuries. *Am J Sports Med* 2014;42:177-186.
25. Oh YK, Kreinbrink JL, Wojtys EM, Ashton-Miller JA. Effect of axial tibial torque direction on ACL relative strain and strain rate in an in vitro simulated pivot landing. *J Orthop Res* 2012;30:528-534.
26. Oh YK, Lipps DB, Ashton-Miller JA, Wojtys EM. What strains the anterior cruciate ligament during a pivot landing? *Am J Sports Med* 2012;40:574-583.
27. Beaulieu ML, Oh YK, Bedi A, Ashton-Miller JA, Wojtys EM. Does limited internal femoral rotation increase peak anterior cruciate ligament strain during a simulated pivot landing? *Am J Sports Med* 2014;42:2955-2963.
28. Beaulieu ML, Wojtys EM, Ashton-Miller JA. Risk of anterior cruciate ligament fatigue failure is increased by limited internal femoral rotation during in vitro repeated pivot landings. *Am J Sports Med* 2015;43:2233-2241.
29. Sankar WN, Laird CT, Baldwin KD. Hip range of motion in children: What is the norm? *J Pediatr Orthop* 2012;32:399-405.
30. Nepple JJ, Prather H, Trousdale RT, et al. Diagnostic imaging of femoroacetabular impingement. *J Am Acad Orthop Surg* 2013;21:S20-S26 (suppl 1).
31. Bedi A, Dolan M, Leunig M, Kelly BT. Static and dynamic mechanical causes of hip pain. *Arthroscopy* 2011;27:235-251.
32. de Castro JV, Machado KC, Scaramussa K, Gomes JL. Incidence of decreased hip range of motion in youth soccer players and response to a stretching program: A randomized clinical trial. *J Sport Rehabil* 2013;22:100-107.
33. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med* 2005;33:1003-1010.
34. Palmer K, Hebron C, Williams JM. A randomised trial into the effect of an isolated hip abductor strengthening programme and a functional motor control programme on knee kinematics and hip muscle strength. *BMC Musculoskelet Disord* 2015;16:105.
35. Bedi A, Dolan M, Hetsroni I, et al. Surgical treatment of femoroacetabular impingement improves hip kinematics: A computer-assisted model. *Am J Sports Med* 2011;39:43S-49S (suppl).
36. Kelly BT, Bedi A, Robertson CM, Dela Torre K, Giveans MR, Larson CM. Alterations in internal rotation and alpha angles are associated with arthroscopic cam decompression in the hip. *Am J Sports Med* 2012;40:1107-1112.
37. Kubiak-Langer M, Tannast M, Murphy SB, Siebenrock KA, Langlotz F. Range of motion in anterior femoroacetabular impingement. *Clin Orthop Relat Res* 2007;458:117-124.
38. Doege TC, Houston TP. *Guide to the evaluation of permanent impairment*, Ed 4. Chicago: American Medical Association, 1995.
39. Kettunen JA, Kujala UM, Raty H, et al. Factors associated with hip joint rotation in former elite athletes. *Br J Sports Med* 2000;34:44-48.
40. Kouyoumdjian P, Coulomb R, Sanchez T, Asencio G. Clinical evaluation of hip joint rotation range of motion in adults. *Orthop Traumatol Surg Res* 2012;98:17-23.
41. Macedo LG, Magee DJ. Differences in range of motion between dominant and nondominant sides of upper and lower extremities. *J Manipulative Physiol Ther* 2008;31:577-582.
42. Sauers EL, Huxel Bliven KC, Johnson MP, Falsone S, Walters S. Hip and glenohumeral rotational range of motion in healthy professional baseball pitchers and position players. *Am J Sports Med* 2014;42:430-436.
43. Kaneko M, Sakuraba K. Association between femoral anteversion and lower extremity posture upon single-leg landing: Implications for anterior cruciate ligament injury. *J Phys Ther Sci* 2013;25:1213-1217.