



Radiographic Cam Morphology of the Hip May Be Associated with ACL Injury of the Knee: A Case-Control Study

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Purpose: To evaluate femoral and acetabular morphology in patients who underwent anterior cruciate ligament reconstruction (ACLR). **Methods:** A retrospective review of a prospectively collected ACL registry was performed to identify patients with pelvis radiographs before undergoing either primary or revision ACLR between January 2010 and August 2020. Alpha angle (AA), head-neck offset ratio (HNOR), lateral center edge angle (LCEA), and crossover sign (COS) were measured on the operative side. Values were compared to a negative control group that did not significantly differ in age, sex, or body mass index. Univariate analysis and Pearson's correlation coefficient were used to compare groups with significance defined as $P < .05$. **Results:** In total, 114 patients were included (ACL, $n = 38$; control, $n = 76$). Eleven primary and 27 revision ACL reconstructions were identified. The mean AA in patients undergoing primary ACL reconstruction was higher than control ($67.45^\circ \pm 11.30^\circ$ vs $51.5^\circ \pm 10.8^\circ$, $P < .001$). A significantly elevated AA was also found in those undergoing revision ACL surgery ($61.8^\circ \pm 7.51^\circ$ vs $51.5^\circ \pm 10.8^\circ$, $P < .001$). In addition, the HNOR was significantly lower in the ACL group (0.12 ± 0.03 vs 0.14 ± 0.04 , $P = .0304$). Acetabular morphology was similar between groups (LCEA, ACL $31.97^\circ \pm 5.04^\circ$ vs control $30.01^\circ \pm 5.17^\circ$, $P = .0549$; COS, ACL 9 of 38 (23.7%) vs control 18 of 76 (23.7%), $P = 1.00$). **Conclusion:** An association exists between radiographic cam morphology of the hip and patients who previously underwent ACLR. **Level of Evidence:** III, retrospective comparison study.

Anterior cruciate ligament (ACL) tears of the knee are increasingly common injuries, with a reported annual incidence of 68.6 per 100,000 person years.¹ Particularly among adolescents aged 13 to 17 years

old, rates of ACL injury and reconstruction have increased dramatically over the last 2 decades (37%, isolated ACL tears; 107% ACL + meniscal tears).² In a large database study, risk factors for revision ACL reconstruction (ACLR) procedures included the use of allograft, hamstring autografts, male sex, younger age, lower body mass index (BMI), and white race.^{3,4}

Recent literature has focused on the association between altered hip mechanics and ACL injury. A systematic review by Boutris et al.⁵ found multiple clinical studies reporting a significant relationship between decreased hip internal rotation (loss of 10° to 20°) and noncontact ACL tears.⁵ In addition, clinical studies have found an association between cam morphology (decreased femoral head/neck offset) and ACL tears.⁶⁻⁸ The development of cam morphology of the femoral head-neck is more common in athletes who participated in a high volume of impact sports during the process of skeletal maturation.⁹ Cam-type femoroacetabular impingement (FAI) typically results in loss of hip internal rotation, which can place increased strain and lead to fatigue failure of the ACL.¹⁰⁻¹²

Given previous associations between cam morphology and primary ACL tears, it is plausible that

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this relationship will be found in patients undergoing revision ACLR. The purpose of the present study is to evaluate femoral and acetabular morphology in patients who underwent ACLR. Our hypothesis is that patients who previously underwent ACLR will have an increased incidence of cam-type morphology of the hip.

Methods

A retrospective review of a prospectively collected ACL registry was performed to identify patients who received full-length lower extremity radiographs before primary or revision ACLR between January 2010 and August 2020. Patients aged 18 to 45 with standing full-length lower extremity films were identified and used to evaluate femoral and acetabular morphology of the hip on the operative side. Patients with a history of hip disease (FAI or hip dysplasia) or previous hip surgery were not included in the ACL group.

The ACL group was compared to a control group of pelvis x-rays identified via retrospective review of the electronic medical record from the same institution. Full length and standing AP pelvis x-rays were collected from orthopaedic trauma, tumor, and primary care patients who did not have radiographic evidence of hip deformity (i.e., fracture) or disease process of the hip joint (i.e., tumor). This was confirmed by the interpreting radiologist independent from the study. Radiographs of patients aged 18 to 45 were identified. Orthopaedic primary care patients consisted of those presenting for evaluation of back, pelvis, or lower extremity pain, as well as those with various lower extremity injuries other than ACL injury (meniscus tears, cartilage injuries, etc.). Polytrauma patients were not included. Radiographs of patients from total joint arthroplasty or young adult hip clinics (including patients with hip dysplasia or FAI) and those with a history of previous hip surgery for all indications at any institution were excluded from the control group. Only one radiograph for each patient was used. Exclusion criteria were confirmed via review of clinic notes and procedure logs (surgical history).

Two independent reviewers, including a resident orthopaedic surgeon (K.G.) and medical student research fellow (A.L.S.) with experience in young adult hip conditions, measured the alpha angle (AA), head-neck offset ratio (HNOR), lateral center edge angle (LCEA), and crossover sign (COS) to compare femoral and acetabular morphology between groups. The technique described by Gosvig et al.¹³ was used to measure the AA. First, the center of the femoral head was found, and a best-fit circle was drawn around the circumference of the femoral head. A line was then drawn from the center of the best-fit circle along the center of the femoral neck. Starting from the center of the femoral head, a line was drawn across the first point where any bone deviated from the best-fit circle. This represents the point where the bony

abnormality increased the radius of the circle, and the angle between the middle of the femoral neck and this point is considered the AP alpha angle (Fig 1). The AA was taken using a digital goniometer (PACS Imaging, Vue Motion; Carestream Health, Rochester, NY). Previous studies have shown high interrater and intrarater reliability and validity of measuring AA by both experienced and even inexperienced observers.^{14,15} We defined an elevated alpha angle and presence of cam morphology as $\geq 60^\circ$.¹⁶ HNOR was measured on the anteroposterior (AP) pelvis film by drawing three parallel lines: line 1, drawn through the center of the long axis of the femoral neck; line 2, drawn through the anterior most aspect of the femoral neck; and line 3, drawn through the anterior most aspect of the femoral head. The ratio is calculated by measuring the distance between lines 2 and 3 and dividing by the diameter of the femoral head. We determined an HNOR < 0.17 as an indicator of the presence of cam morphology.¹⁷ In addition, LCEA and COS were measured as previously described.¹⁷

Statistical Analysis

Demographic information including age, sex, and BMI were collected for all individuals and compared between groups. Normality was assessed with the Shapiro-Wilk test, which demonstrated that age and BMI were not normally distributed in both groups, and AA was not normally distributed in the control group only; however, only age demonstrated a severe departure from normality. Numerical means were compared using an independent, two-tailed t-test, and categorical data were compared using a χ^2 test. A Wilcoxon rank sum test was also used to compare age. In addition, Pearson's correlation coefficient was used to assess any association between demographic variables and radiographic measurements. For all tests, $P < .05$ was considered statistically significant. Statistical analysis was performed using Excel v.16.43 (Microsoft Inc., Redmond, WA).

Results

Patient Demographics

In the ACL group, 49 patients were initially identified, and 11 patients were excluded for ages < 18 or > 45 years. In the control group, 189 radiographs of patients aged 18-45 were identified, and 94 radiographs remained after exclusion criteria were applied (hip disorder or previous hip surgery, $n = 74$; duplicate patients, $n = 21$). Because of a significant older age in the control group (32.6 vs 28.2 years, $P = .0014$), the age range of the control group was restricted to 18 to 40 years, yielding 76 x-ray films (full-length = 32, trauma = 13, tumor = 24, primary care = 7). In total, 114 patients were included (ACL, $n = 38$; control, $n = 76$). Patient demographics including sex, age, BMI, and operative side were similar between groups (Table 1).

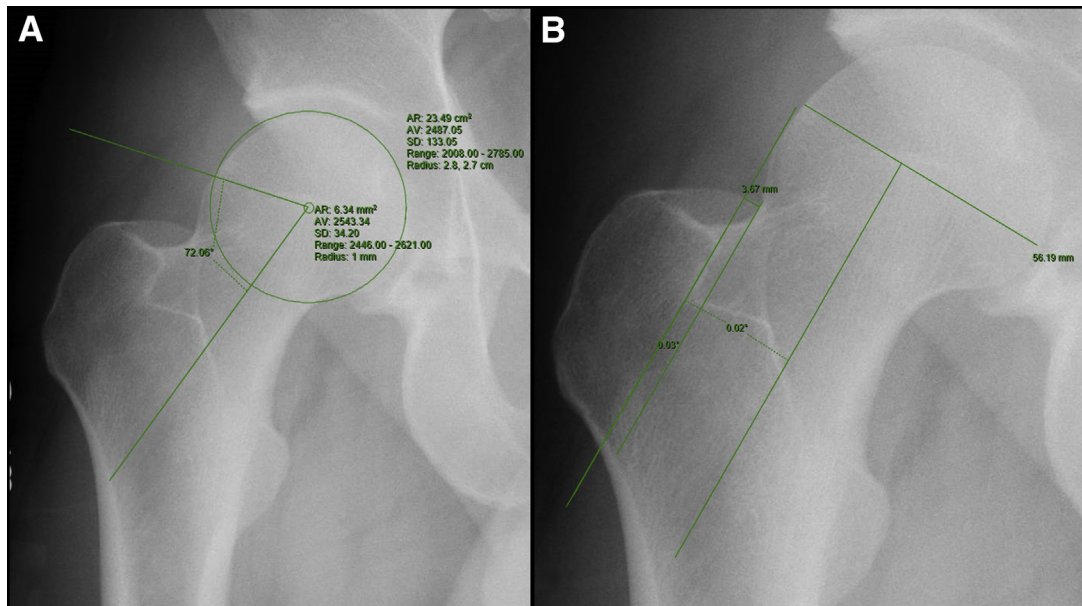


Fig 1. Anteroposterior view of the right hip from the same patient. (A) Depiction of alpha angle (72.06°), and (B) head/neck offset ratio (0.07). Measurements were taken using a digital goniometer (PACS Imaging, Vue Motion; Carestream Health, Rochester, NY).

Femoral Head-Neck Morphology

The AA in patients with history of primary ACL injury ($n = 11$) was found to be increased in comparison to the control group ($67.45^\circ \pm 11.30^\circ$ vs $51.5^\circ \pm 10.8^\circ$, $P < .001$). Sixty-four percent of patients in the primary ACL-injured group had an alpha angle $\geq 60^\circ$ compared to 22% in the control group ($P = .0085$). The odds of having an alpha angle $\geq 60^\circ$ was found to be significantly greater in the primary ACL-injured group as well (odds ratio 6.07; 95% confidence interval, 1.58-23.24; $P = .0084$). The average HNOR was low in both groups (normal < 0.2) but not significantly different between them (0.12 ± 0.03 vs 0.14 ± 0.03 , $P = .1677$).

Patients who sustained recurrent ACL-injury and required revision surgery ($n = 27$) were also found to have an elevated alpha angle compared to the control group ($61.8^\circ \pm 7.51^\circ$ vs $51.5^\circ \pm 10.8^\circ$, $P < .001$). The proportion of patients with an alpha angle $\geq 60^\circ$ was also higher in the revision ACL group (56% vs 22%, $P = .003$; odds ratio 4.34, 1.71-11.01, $P < .001$). The

difference in HNOR between the revision ACL and control groups did not reach statistical significance (0.123 ± 0.04 vs 0.138 ± 0.03 , $P = .0605$).

Overall, the mean alpha angle was greater in the ACL-injured group compared to control ($63.4^\circ \pm 9.0^\circ$ vs $51.5^\circ \pm 10.8^\circ$, $P < .001$) (Fig 2). And in total, the proportion of patients with an AA $\geq 60^\circ$ was significantly higher in the ACL-injured group (57.9% vs 22.4%, $P < .001$). The mean alpha angle was not significantly different between who underwent primary or revision ACLR (primary, $67.45^\circ \pm 11.30^\circ$ vs $61.8^\circ \pm 7.51^\circ$, $P = .1477$).

In the entire ACL cohort, males tended to have higher alpha angles, but this did not reach significance ($r = 0.2964$, $P = .0708$). Older age ($r = 0.0710$, $P = .6718$) and elevated BMI ($r = -0.2378$, $P = .1505$) did not correlate with AA. In the control group, male sex correlated with higher AA ($r = 0.548$, $P < .001$), whereas older age ($r = 0.1261$, $P = .2776$) and elevated BMI ($r = 0.1939$, $P = .0933$) did not significantly correlate with higher AA.

Table 1. Patient Demographics

	Control (n = 76)	ACL* (n = 38)	P Value
Sex (female)	39 (51.3%)	19 (50%)	.8961
Age (y) [†]	30.1 ± 7.41 (31.5, 18-40)	28.2 ± 8.87 (26.1, 18-45)	.2656
BMI [†]	28.44 ± 7.21 (16.45-45.44)	27.9 ± 5.83 (18.74-42.26)	.1926 [‡]
Operative side (right)	40 (52.6%)	19 (50%)	.6631
			.7940

ACL, anterior cruciate ligament; BMI, body mass index.

*Includes primary ($n = 11$) and revision ($n = 27$) ACL reconstructions.

[†]Mean \pm standard deviation (median, range).

[‡]Results from Wilcoxon rank sum test.

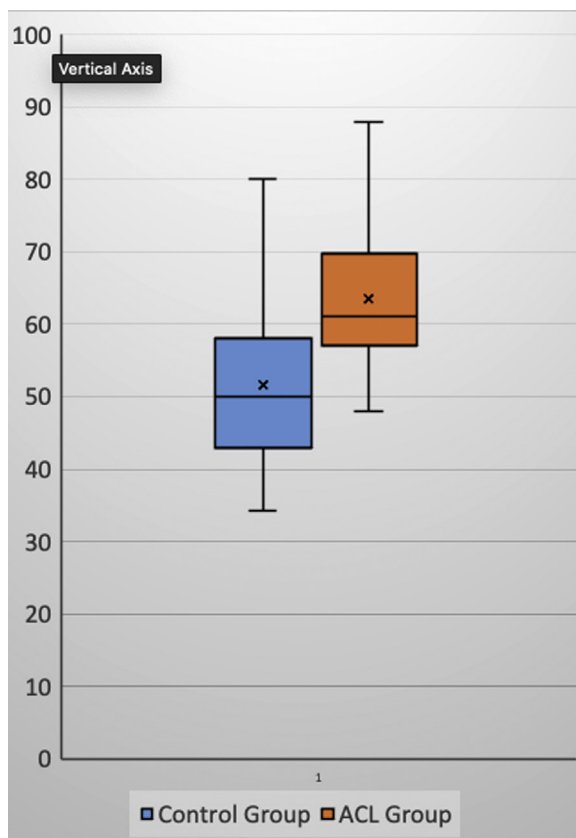


Fig 2. Box and whisker plot of median \pm interquartile range (IQR) of alpha angle (AA, $^{\circ}$) for control (median 50° , IQR 42.9° - 57°) and anterior cruciate ligament (ACL) groups (median 61° , IQR 58.1° - 69.6°). Mean AA represented by point X (control, 51.5° ; ACL, 63.4°).

Acetabular Morphology

The mean LCEA was within normal limits for primary ACL-injured patients and the control group (ACL $30.55^{\circ} \pm 5.63^{\circ}$ vs control $30.00^{\circ} \pm 5.63^{\circ}$, $P = .7687$). The mean LCEA was also within normal limits in patients who underwent revision ACL reconstruction ($32.78^{\circ} \pm 5.24^{\circ}$ vs $30.00^{\circ} \pm 5.63^{\circ}$), and this slight difference was found to be significant ($P = .0222$). Overall, LCEA did not significantly differ between the ACL-injured group vs control ($31.97^{\circ} \pm 5.04^{\circ}$ vs $30.01^{\circ} \pm 5.17^{\circ}$, $P = .0549$). In the entire ACL cohort, patients with higher AA tended to have lower LCEA ($r = -0.2631$), but this relationship was not statistically significant ($P = .1105$). There was no significant association between LCEA and AA in the control group ($r = 0.0564$, $P = .6286$). The presence of a crossover sign was not significantly different between groups as well (ACL 9 of 38 [23.7%] vs control 18 of 76 [23.7%], $P = 1.00$).

Discussion

The principal finding of this study was the association found between radiographic cam morphology and patients undergoing ACLR, which confirms our hypothesis.

The average ipsilateral alpha angle was significantly higher in patients who underwent primary and revision ACLR. The odds of having an alpha angle $\geq 60^{\circ}$ was significantly (6 times) greater in the primary ACLR group. Acetabular morphology was not significantly different in patients with previous ACL injury. These findings were made in comparison to a diverse group of control subjects who did not differ significantly in age, sex, or BMI.

The association between altered hip mechanics, cam-type FAI, and ACL tears has been established.^{5-7,12,18} Gomes et al.¹⁸ previously investigated hip mechanics in a group of soccer players, and they found a strong association between decreased hip internal rotation and non-contact ACL ruptures. Subsequently, Philippon et al.⁶ found an association between diminished femoral head-neck offset and primary ACL injury on the ipsilateral side. Bedi et al.¹² also investigated whether a correlation exists between FAI and history of ACL tear in a group of high-contact athletes, and they found a correlation between athletes with reduced internal rotation of the hip and previous ipsilateral and contralateral ACL injury. In addition, they demonstrated the adverse effects of FAI on ACL strain with an in silico model, showing that ACL strain increases as hip internal rotation decreases as a result of mechanical hip impingement.¹² The present study further demonstrates the association between radiographic cam morphology and previous ACL injury—a finding that has limited clinical evidence.⁶ Interestingly, the odds of having an AA $\geq 60^{\circ}$ in the setting of primary ACLR were slightly increased in comparison to revision ACLR. However, the mean alpha angle between primary and revision ACLR were not significantly different ($P = .1477$). It may be plausible for surgeons to evaluate for cam morphology in patients with initial ACL injury because of the associations between limited femoral internal rotation, radiographic cam morphology, and ACL tears have now been further established.⁵ Furthermore, cam-type FAI has been established as a cause of early-onset hip osteoarthritis.^{19,20} Earlier identification and correction of cam-type FAI syndrome at the time of initial ACL injury could potentially delay the development of hip osteoarthritis.

A cam deformity is one cause of decreased femoral internal rotation in flexion.²¹ It must be recognized that acetabular retroversion and low femoral anteversion can also decrease hip internal rotation in flexion and contribute to FAI syndrome.²² In the present study, acetabular retroversion was evaluated with the presence of a crossover sign, which was not significantly different between the ACL and control groups. The degree of femoral version was not assessed in this study. In a prospective analysis of 440 hips, Kraeutler et al.²² demonstrated that the degree of femoral version significantly outweighs the effect of cam deformities in terms of hip internal rotation. There is a paucity of literature

evaluating the relationship between femoral version and ACL injury. Biomechanically, Beaulieu et al.¹⁰ demonstrated that an abrupt limitation in femoral internal rotation—such as in cam-type FAI or femoral retroversion—during a pivot landing increases strain of ACL and thus increases the risk of ACL injury. Amrae et al.²³ evaluated several clinical factors of lower extremity alignment in patients with history of complete ACL tears, including femoral version. They found that an increase in anteversion by 1° corresponded to a 1.78 increase in odds of previous ACL injury; however, hip anteversion was evaluated with Craig's test rather than 3-dimensional rotational imaging.²³ Future research should investigate these relationships and the mechanism between hip morphology, femoral version, and ACL injury, likely how decreased femoral internal rotation combined with abduction at the knee and anterior tibial translation results in increase in ACL strain.

Studies have also demonstrated that cam morphology develops more commonly in young athletes compared to non-athlete populations, potentially as a result of increased stress placed on the capital femoral physis during the process of skeletal maturity.^{9,24,25} Naturally, young athletic populations are at higher risk of ACL injury in comparison to more sedentary populations. Thus it is difficult to determine whether the associations found in the present study are due to differences in activity levels, which places the ACL group independently at risk for both cam morphology and ACL injury. Information regarding adolescent activity levels would be needed in future studies to adequately control for this relationship.

Limitations

There are several limitations to the present study. First, the study's retrospective nature precludes the ability to establish causation between femoral cam morphology, decreased femoral internal rotation, and greater risk of ACL injury. In addition, the number of available patients with full-length lower extremity films, particularly in the setting of primary ACLR, limited our ability to compare those who underwent primary and revision ACLR. Using AP radiographs as opposed to lateral views (Dunn or Frog leg) to determine the presence of cam morphology is also a limitation. Additionally, true acetabular retroversion is defined as a positive COS, positive posterior wall sign, and positive ischial spine sign, which were not all collected because of the use of full-length radiographs. Measurements were also completed by 2 reviewers who were not blinded to study groups and without interrater or intrarater reliability analysis. Selecting controls on the basis of "nonremarkable" radiographs creates a high risk of selection bias. Potential variability exists because of using both full-length and AP pelvis views in the control group. The small sample size also

introduces some risk of finding a type II error. Furthermore, as stated above, cam morphology and ACL tears are 2 common findings in athletic patient populations, and this strong association could be related to the activity level of the individuals studied. Future prospective studies of athletic populations are needed to more conclusively define the relationship between FAI syndrome and ACL tears.

Conclusion

An association exists between radiographic cam morphology of the hip and patients who previously underwent ACLR.

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