Medial Subluxation of the Tibia After Anterior Cruciate Ligament Rupture as Revealed by Standing Radiographs and Comparison With a Cadaveric Model

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Background: Biomechanical studies indicate that the tibia shifts medially and has a more valgus orientation in the anterior cruciate ligament (ACL)–deficient knee. However, it is not known whether these differences can be detected on standing radiographs.

Purpose: To determine whether medial subluxation and more changes in coronal alignment of the tibia are detectable in both weightbearing radiographs and a cadaveric model simulating quiet standing.

Study Design: Case series; Level of evidence, 4, and Descriptive laboratory study.

Methods: Radiographic data were available for a cross-section of 74 patients with unilateral ACL tears. Tibial subluxation and coronal limb alignment were measured on hip-to-ankle weightbearing radiographs. Eight cadaveric knees were mounted on a 6 degree of freedom robot. Mediolateral position and varus-valgus alignment of the tibia relative to the femur were measured in response to 300-N axial compression simulating quiet standing at 5° and 15° of flexion with the ACL intact and sectioned.

Results: Across all 74 patients included in the clinical study, the ACL-injured knee experienced 1.6 ± 2.3 mm (mean ± SD) of medial tibial subluxation compared with the contralateral uninjured knee ($P < .001$). The 24 patients with isolated ACL rupture exhibited 2.0 ± 1.8 mm of medial subluxation ($P < .001$). The mean coronal alignment of all 74 patients in the study was 0.7° ± 2.8° varus in the injured limb and 1.3° ± 2.6° varus in the uninjured contralateral limb ($P = .0187$). In the cadaveric model, the tibia translated 0.4 ± 0.5 mm more medially after sectioning of the ACL at 15° of flexion ($P = .0485$); however, no changes in coronal alignment were detected.

Conclusion: The tibia shifts medially and is less varus in the ACL-deficient knee on standing radiographs. The medial tibial shift is reproduced in an axially loaded cadaveric model.

Clinical Relevance: Medial tibiofemoral subluxation seen on frontal plane standing radiograph is an underappreciated sequela of isolated ACL rupture. The ability of ACL reconstruction to restore this aspect of ACL injury is not well understood and should be investigated further. Cadaveric models may be used to directly measure the mechanical effect of subtle changes in mediolateral position on articular contact stress as an indicator of the importance of this finding.

Keywords: anterior cruciate ligament; knee; biomechanics

The anterior cruciate ligament (ACL) has an oblique orientation, indicating that it resists loads in the frontal plane including those that act to shift the tibia medially and rotate the tibia into valgus.[5,11,13] High congruence of the tibial spine and the femoral notch in the frontal plane may exacerbate the effect of subtle changes in tibiofemoral position in this plane after ACL injury on tibiofemoral contact mechanics. Altered contact mechanics after joint injury can play an important role in the onset and progression of osteoarthritis (OA),[18] including peaking of the tibial spine and osteophyte formation on the medial side of the femoral notch.[3,6,9] Therefore, understanding the effect of ACL injury on the frontal plane position and orientation of the tibia is critical.

Alterations in the mediolateral position of the tibia in the ACL-deficient knee have been well-documented in previous cadaveric experiments and in vivo studies by use of biplanar fluoroscopy.[11-13] Unfortunately, these approaches cannot be readily adapted to large cohorts of patients. In contrast, data describing the mediolateral position of the tibia could be obtained from standing radiographs, which

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are recorded in many patients with ACL rupture as a routine part of their clinical examination.

A measure of the position of the tibia relative to the femur in the frontal plane obtained from full-length standing radiographs has recently been developed and may be readily adapted to large numbers of patients.[16] This measure, named *tibiofemoral subluxation*, describes the position of the tibia relative to the femur in a direction that is perpendicular to the long axis of the tibia and was previously used to distinguish between a cohort of individuals with no radiographic signs of knee OA and a cohort of patients with arthritis isolated to a single compartment.[16] It may be a candidate to describe the effects of ACL injury and reconstruction on the frontal plane position of the knees.

The goal of this study was to measure the position and orientation of the tibia relative to the femur in the frontal plane in individuals with unilateral ACL injury. We hypothesized that tibiofemoral subluxation would increase in the ACL-deficient patients during standing radiographs compared with the contralateral, uninjured joint. If proven correct, this would identify an accessible clinical parameter for differentiating ACL-competent and ACL-deficient patients. We further hypothesized that we would detect changes in the frontal plane position and orientation of axially loaded cadaveric specimens simulating quiet standing. Successfully proving this hypothesis would allow subsequent measurement of parameters that are difficult to obtain in vivo, such as contact stress, to better understand the effect of clinically observed shifts in the mediolateral position of the tibia.

METHODS

Radiographic Study

After we obtained institutional review board approval, we performed an electronic database search for patients who sustained a complete ACL disruption between April 2010 and July 2013, yielding 93 patients. Inclusion criteria for the study were (1) patients who had weightbearing hip-to-ankle radiographs of both knees and (2) patients with complete ACL tears confirmed by arthroscopic examination. Exclusion criteria were (1) history of knee trauma before the ACL injury, inflammatory arthropathy, or degenerative changes in either knee; (2) history of injury in the contralateral knee; (3) history of surgical procedure in the contralateral knee; (4) multiligament knee injury; and (5) congenital deformities. All findings of secondary meniscal and chondral damage diagnosed during knee arthroscopy were recorded. Standing radiographs were performed with the standard protocol that is used at our institution. The patients stood barefoot with their back against an upright bucky, which held the radiograph grid and cassette. Patients were instructed to stand normally with the knee fully extended and centered in the bucky and their body weight distributed evenly between both limbs. The knee cap and foot were aligned with the direction of the x-ray beam. The x-ray beam was centered on the distal pole of the patella and oriented so that the image was aligned parallel to the tibial joint line in the frontal plane. Source to image distance was standardized to 122 cm. A standard 25 ± 0.25–mm AISI 316 stainless steel calibration sphere (Calibration Unit; Sectra) was included in each image as a reference to account for any magnification effects.

Radiographs of both left and right knees of each patient were assessed for projection error that could confound our measurement of mediolateral subluxation. To assess rotation of the tibia, we used a method based on overlap of the fibula head and tibia previously published by Maderbacher et al.[15] If the difference in tibial rotation between right and left limbs was greater than 5°, the patient was excluded.

For the hip-to-ankle weightbearing radiographs, limb alignment was measured as the angle between a line joining the center of the femoral head to the center of the distal femur and another line joining the center of the tibial plateau to the center of the talus. Tibiofemoral subluxation was previously defined as the perpendicular distance between the long axis of the tibia and a second parallel line originating at the most proximal aspect of the femoral intercondylar notch.[16] The long axis of the tibia was defined as the line connecting the centers of the circles that fit the talar dome and the proximal tibial plateau, respectively. This method was previously found to have interobserver reliability, as quantified by an interclass correlation coefficient of 0.86.[16] Tibiofemoral subluxation was defined to be positive if the line from the apex of the intercondylar notch fell medial to the tibial mechanical axis (Figure 1). The comparison with the uninjured contralateral knee was based on previous findings that right and left knees of patients exhibit a high level of morphological similarity.[1,4,17]

Cadaveric Biomechanical Study

A controlled biomechanical study was undertaken to identify whether isolated ACL sectioning reflected radiographic changes independent of additional confounding variables such as weightbearing differences between limbs and clinical symptoms such as pain and associated injury. Eight cadaveric knees (mean ± SD age, 51 ± 11 years; range, 29-64 years) were used in this portion of the study. Knees were examined clinically and inspected through a medial

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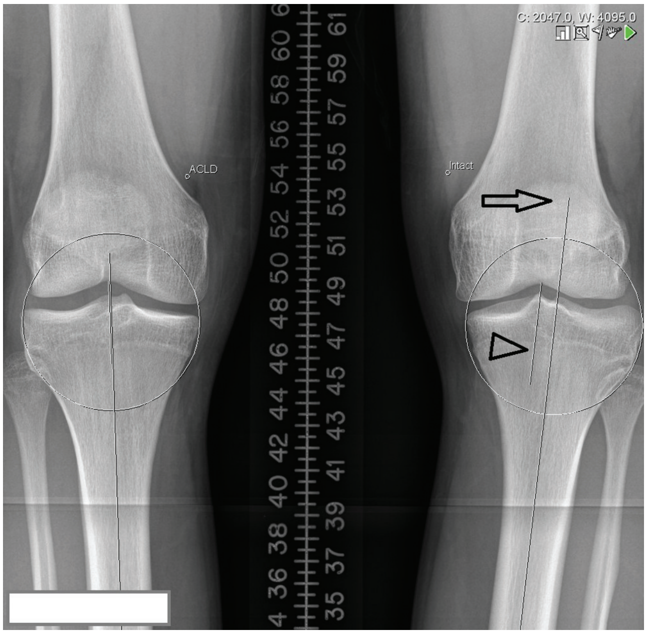

Figure 1. Anteroposterior weightbearing radiograph. The anterior cruciate ligament–deficient knee (left) has medial translation of the tibiofemoral mechanical axis when compared with the intact knee (right). The arrow points to the line that identifies the long axis of the tibia. The arrowhead points to a line parallel to the long axis of the tibia that passes through the most proximal aspect of the femoral intercondylar notch.

parapatellar arthrotomy and via computed tomography. Any specimens with bony deformities, osteoarthritis, flexion contractures, ACL deficiency, or meniscal injuries were excluded. The tibia and femur were sectioned midshaft and potted in bonding cement by use of cylinders (Bondo, 3M) that were 2 inches in diameter. The remaining proximal portion of the fibula was fixed to the tibia in its anatomic orientation with a wood screw. The tibia was then mounted to a 6 degree of freedom industrial robot (ZX165U; Kawasaki Robotics), and the femur was mounted to a pedestal that was rigidly fixed to the ground. The knee was mounted in full extension as determined by visual inspection. The industrial robot included a universal force-moment sensor (Theta; ATI Industrial Automation) that enabled measurement of the loads and torques generated at the knee joint.[11]

Coordinate systems were assigned to the tibia and femur by use of anatomic landmarks as described previously.[11] The femoral epicondyles defined the flexion extension axis, while the midpoint of the line formed by the distal insertion of the lateral collateral ligament (LCL) and the midsubstance of the medial collateral ligament (MCL) together with lateral aspect of the distal end of the tibial shaft delineated the long axis of the tibia.[11] The anterior-posterior axis was the common perpendicular of the flexion axis and the long axis. These definitions were used to identify the position and orientation of the tibia relative to the femur according to a common convention adapted from Grood and Suntay.[8] Tibiofemoral translations were described relative to a point located at the bisection of the femoral condyles.[11] Subsequently, the path of passive knee flexion was determined by identifying the position and orientation that achieved predetermined knee loads of 10 N compression and no force or torque in the remaining directions within prescribed tolerances of 5 N and 0.5 N·m, respectively. The robot minimized the reaction loads at the knee to satisfy these loading criteria at 1° increments. The intact knee was subsequently preconditioned 10 times under anterior loads of 134 N at 30° of flexion (a simulated Lachman test) and under combined moments of 8 N·m and 4 N·m in abduction and internal rotation, respectively, at 15° of flexion (a simulated pivot-shift test).

Weightbearing conditions were simulated by applying axial compression of 300 N at 5° and 15° of flexion. Loads in the remaining directions including varus-valgus were minimized. The axial load represented about half body weight, assuming that load was distributed evenly between both limbs during standing. The compressive load was directed along the long axis of the tibia as defined by the tibial anatomic landmarks described above. The flexion angles were chosen based on common radiographic positions after ACL injury.[3] Frontal plane kinematics, including our primary outcomes, mediolateral translation and varus-valgus angulation of the tibia relative to the femur, was recorded with the ACL intact and after it was sectioned.

Statistical Methods

In the clinical study, means, standard deviations, and 95% confidence intervals were calculated for mediolateral tibial subluxation and coronal plane knee alignment. After the Kolmogorov-Smirnov test was used to check for normality, 2-tailed paired *t* tests were used to compare the motions of the injured limb to the uninjured, contralateral limb. Differences were considered significant when $P < .05$.

In the cadaveric biomechanical study, means and standard deviations were calculated for mediolateral subluxation and varus-valgus alignment. After the Kolmogorov-Smirnov test was used to check for normality, 2-tailed paired *t* tests were used to compare the motions of each specimen before and after sectioning of the ACL. Differences were considered significant at $P < .05$. All analyses were performed with commercial statistics software (SigmaPlot 12.3; Systat Software Inc).

RESULTS

Thirteen patients were excluded because radiographic images exhibited differences in tibial rotation greater than 5° between right and left limbs. The average difference between right and left limbs in tibial rotation was 7.3° ± 2.0° in the 13 excluded patients compared with 0.2° ± 1.0° in the knees that were included. Six additional patients were excluded due to contralateral ACL reconstruction.

Complete sets of retrospective data were available in 74 patients (148 knees). The mean age of these 74 patients (±SD) at the time of evaluation was 32 ± 10 years. Males

TABLE 1
Patient Demographics[a]

Injury Type	No. of Patients	Age, Mean ± SD	No. of Males/Females
Isolated ACL rupture	24	32 ± 10	9/15
ACL + any meniscal tear	44	33 ± 10	24/20
ACL + medial meniscal tear	22	34 ± 11	11/11
ACL + lateral meniscal tear	15	34 ± 10	8/7
ACL + bilateral meniscal tears	7	28 ± 7	5/2
ACL + any chondral damage	6	34 ± 9	4/2
All patients	74	32 ± 10	37/37

[a] ACL, anterior cruciate ligament.

TABLE 2
Medial-Tibial Subluxation (in Millimeters)[a]

	Mean ± Std Dev (95% CI)			
Injury Type	Uninjured Contralateral Leg	Injured Leg	Difference[b]	*P*-value
Isolated ACL rupture (n = 24)	5.0 ± 2.0 (4.2-5.8)	3.0 ± 1.4 (2.4-3.6)	2.0 ± 1.8 (1.3-2.8)	**<0.001**
ACL + any meniscal tear (n = 44)	5.1 ± 2.0 (4.5-5.7)	3.7 ± 2.2 (3.0-4.3)	1.4 ± 2.4 (0.7-2.2)	**<0.001**
ACL + medial meniscal tear (n = 22)	4.5 ± 2.1 (3.6-5.4)	3.8 ± 2.0 (2.9-4.6)	0.7 ± 1.7 (–0.2-1.3)	0.063
ACL + lateral meniscal tear (n = 15)	5.8 ± 1.8 (4.9-6.7)	3.8 ± 2.6 (2.4-5.1)	2.0 ± 2.9 (0.5-3.5)	**0.018**
ACL + bilateral meniscal tears (n = 7)	5.6 ± 1.6 (4.4-6.8)	3.1 ± 1.5 (2.0-4.1)	2.5 ± 2.9 (0.4-4.6)	0.058
ACL + any chondral damage (n = 6)	2.6 ± 1.8 (1.1-4.0)	2.0 ± 1.8 (0.5-3.5)	0.6 ± 2.5 (–1.5-2.6)	0.607
All patients (N = 74)	4.9 ± 2.1 (4.4-5.3)	3.3 ± 2.0 (2.9-3.8)	1.6 ± 2.3 (1.0-2.1)	**<0.001**

[a] Values are expressed as mean ± 1 SD (95% CI). Bolded P values indicate statistically significant difference between groups ($P < .05$). ACL, anterior cruciate ligament.

[b] A positive number indicates medial subluxation of the ACL-deficient knee relative to the uninjured contralateral knee.

comprised 50% (n = 37) of the study population (Table 1). In 47 patients, the right knee was ACL deficient. There were 24 knees with isolated ACL rupture, 44 knees had ACL rupture combined with meniscal damage, and 6 knees had ACL injury and additional chondral damage. At the time of the arthroscopic procedure, 2 patients had chondral injuries of the medial femoral condyle that required intervention (chondroplasty or osteochondral allograft transfer [OATS; Arthrex]), and 1 patient had chondral damage of the lateral femoral condyle. Three patients had type 4 patellofemoral chondral injuries.

Individuals suffering isolated ACL rupture were medially subluxated 2.0 ± 1.8 mm ($P < .001$) compared with their uninjured contralateral limb (Table 2). Those with ACL rupture combined with meniscal injury of any kind were medially subluxated 1.4 ± 2.4 mm relative to their uninjured contralateral limb ($P < .001$). Patients with ACL rupture and concomitant injury to only the lateral meniscus exhibited medial subluxation averaging 2.0 ± 2.9 mm ($P = .018$). Across all 74 patients included in the clinical study, the injured knee experienced 1.6 ± 2.3 mm of medial tibial subluxation compared with the contralateral uninjured knee ($P < .001$).

Patients with ACL rupture and any type of meniscal tear were in 0.7° ± 2.1° less varus compared with the uninjured, contralateral limb ($P = .030$) (Table 3). Individuals who tore their ACL and sustained tears in both menisci exhibited 1.4° ± 1.4° less varus compared with the uninjured contralateral knee ($P = .039$). Across all 74 patients included in the clinical study, the injured knee was in 0.6° ± 2.1° less varus than their uninjured contralateral limb ($P = .018$).

In the axially loaded cadaveric model, sectioning the ACL caused the tibia to translate medially an additional 0.4 ± 0.5 mm compared with the ACL-competent knee at 15° of flexion ($P = .0485$). No other differences were detected (Table 4).

DISCUSSION

ACL-deficient knees had medial subluxation of the tibia and decreased varus alignment on weightbearing radiographs. This held true in knees with isolated ACL injuries and in knees with ACL injury combined with injury to either the medial or lateral meniscus or injury to both menisci. Our cadaveric biomechanical experiment simulating weightbearing also showed increased medial tibial translation and valgus angulation after isolated sectioning of the ACL.

This novel clinical measure of mediolateral subluxation determined from standing radiograph can be easily obtained in large numbers of patients; therefore, it provides an additional quantitative and objective clinical benchmark beyond current methods to characterize ACL injury. Prospective assessment of subjects before and after

TABLE 3
Valgus Alignment (in Degrees)[a]

	Mean ± Std Dev (95% CI)			
Injury Type	Uninjured Contralateral Leg	Injured Leg	Difference[b]	*P*-value
Isolated ACL rupture (n = 24)	1.0 ± 2.6 (–0.1-2.0)	0.2 ± 3.1 (–1.0-1.4)	0.7 ± 2.2 (–0.1-1.6)	0.109
ACL + any meniscal tear (n = 44)	1.5 ± 2.6 (0.8-2.3)	0.8 ± 2.6 (0.1-1.6)	0.7 ± 2.1 (0.1-1.3)	**0.030**
ACL + medial meniscal tear (n = 22)	1.1 ± 2.3 (0.2-2.1)	0.7 ± 2.1 (–0.2-1.6)	0.5 ± 1.4 (–0.1-1.0)	0.144
ACL + lateral meniscal tear (n = 15)	1.9 ± 3.4 (0.2-3.6)	1.2 ± 3.5 (–0.6-2.9)	0.8 ± 3.1 (–0.8-2.3)	0.342
ACL + bilateral meniscal tears (n = 7)	2.0 ± 1.6 (0.8-3.1)	0.6 ± 1.4 (–0.4-1.6)	1.4 ± 1.4 (0.3-2.4)	**0.039**
ACL + any chondral damage (n = 6)	0.9 ± 2.5 (–1.1-2.8)	1.7 ± 3.1 (–0.7-4.2)	–0.9 ± 1.8 (–2.3-0.6)	0.308
All patients (N = 74)	1.3 ± 2.6 (0.7-1.9)	0.7 ± 2.8 (0.1-1.3)	0.6 ± 2.1 (0.1-1.1)	**0.018**

[a] Values are expressed as mean ± 1 SD (95% CI). Bolded *P* values indicate statistically significant difference between groups ($P < .05$). ACL, anterior cruciate ligament.

[b] A positive number indicates less varus angulation of the tibia of the ACL-deficient knee relative to the uninjured contralateral knee.

TABLE 4
Change in Mediolateral Position and Varus-Valgus Alignment After Sectioning of the ACL in Response to 300-N Compression[a]

	Difference[b]	*P*
5° of flexion		
Mediolateral subluxation, mm	0.2 ± 0.2 (0.0 to 0.3)	.0828
Varus-valgus alignment, deg	–0.0 ± 0.1 (–0.1 to 0.1)	.520
15° of flexion		
Mediolateral subluxation, mm	0.4 ± 0.5 (0.1 to 0.7)	.0485
Varus-valgus alignment, deg	0.1 ± 0.4 (–0.2 to 0.4)	.550

[a] Values are expressed as mean ± 1 SD (95% CI). ACL, anterior cruciate ligament.

[b] A negative number indicates increased medial translation after sectioning the ACL; a positive number indicates increased valgus angulation after sectioning the ACL.

ACL rupture is needed to better determine whether ACL injury is causally related to ML subluxation. A prospective study is also needed to determine whether the amount of ML subluxation is a risk factor for posttraumatic osteoarthritis and whether it negatively affects functional outcomes. This novel measure could be used as part of a comprehensive assessment of the effectiveness of ACL reconstruction procedures.

Our finding of decreased varus alignment during standing radiography in ACL-deficient patients could represent a precursor of OA because increasing valgus misalignment has been identified as a predictor of lateral cartilage and meniscal damage.[7,19] Felson et al[7] reported that even small valgus misalignments of 1.1° to 3° were associated with an increased risk of subsequent radiographic progression of OA in those with preexisting OA. Although ACL injury decreased varus alignment by only 0.6° in our study, coronal alignment might be an important measure to monitor over time in the ACL-deficient population.

We speculate that medial tibial subluxation could be an important factor in joint degeneration after ACL injury because the relatively small amounts of medial tibial subluxation observed in the clinical and the cadaveric components of this study could lead to altered loading of the medial side of the knee. Even small translations occurring in the highly congruent femoral notch and the tibial spine could induce large changes in contact location. Moreover, medial loads that were previously resisted by the ACL based on its oblique orientation could be transferred to the articular surfaces in the ACL-deficient knee. These factors may help explain the clinically observed bony remodeling that occurs at the medial tibial spine and the lateral wall of the medial femoral condyle in the ACL-deficient knee.[3,6,9] Furthermore, recent studies have highlighted the important role that joint incongruence plays in altered contact stress and subsequent joint degeneration.[2,18] Evaluation of contact stress in our cadaveric model will help us further understand the role of tibial subluxation on altered articular contact mechanics. Finally, our study indicates that bilateral and lateral meniscal tears in combination with ACL rupture also result in medial subluxation of the tibia. This finding suggests that the menisci may also play a role in stabilizing the knee in the mediolateral direction; however, further biomechanical study is needed to substantiate this speculation.

Our findings in both the cadaveric model and the clinical study of increased medial translation in the ACL-deficient knee are in agreement with most previous in vivo and in vitro work. Defrate et al[5] reported that during a weightbearing lunge, patients exhibited about 1 mm of medial tibial translation compared with the uninjured contralateral limb between 15° and 90° of knee flexion. Li et al[13] reported that similar increases in medial translation occurred after sectioning of the ACL in a cadaveric model while quadriceps and hamstring loads were applied at 15° and 30° of flexion. In contrast to our findings, lateral tibial translation was measured after sectioning of the ACL in response to 1600 N of axial load at 15° and 30° of flexion in a previous study by Liu-Barba et al.[14] This discrepancy may be a result of slight variations in the orientation of the applied axial load, which could drive the tibia medially or laterally under the high axial loads that were about twice body weight. We speculate that anatomic differences between groups of cadavers in these disparate studies such as tibial slope in the frontal plane could also influence frontal plane motion in response to compressive loads. For example, axial loads applied to a more laterally sloped tibia could drive the tibia more medially. Finally, the medial translation measured in our cadaveric model was smaller than what was observed in our patient cohort with isolated ACL rupture. The difference in magnitude of medial translation and failure to identify decreased varus angulation of the tibia in our cadaveric model may have occurred because the loads applied to the tibia in the cadaveric model differ from those that take place during in vivo quiet standing.

Our findings of mean varus alignment of the uninjured contralateral knees of 1.3° across all patients in the study (Table 3) are similar to previous reports of the alignment of the tibiofemoral mechanical axis in a healthy cohort, which was 1.2° of varus.[10] Interestingly, in the current study, the ACL-deficient knees had significantly less varus rotation (0.7°); thus, the knees are in relative valgus compared with the intact knees. Similarly, valgus rotation increased by about 1° when a quadriceps load was applied after ACL sectioning in a cadaveric model.[13]

This study has limitations. First, a prospective study including radiographs of the limb before and after ACL injury would be superior to our retrospective cross-sectional study. However, our clinical study based on matched analysis of injured and uninjured limbs of a single patient has yielded important information at little cost, which could provide the basis for more time-consuming and expensive prospective studies. Our comparison with the uninjured contralateral knee is based on the assumption that the anatomic features of left and right knees are similar. This assumption is supported by several studies.[1,4,17] Dargel et al[4] studied the anatomic differences between the right and the left lower limbs in 20 paired cadaveric knees. The authors identified no statistical differences between the right and the left leg in bony (femur length, distal condyles, and proximal tibia) and soft tissue dimensions (cruciate ligaments and menisci). Importantly, side-to-side differences in the width of the distal femur and in the width of the proximal tibia were no more 0.8 mm.[4] This anatomic difference would not alter our conclusions because our findings of medial subluxation after ACL injury averaged 1.75 to 2.5 times larger than this side-to-side difference (Table 2). Furthermore, records of knee stability via KT-1000 arthrometric measurements or pivot-shift grade were not available in our cohort; therefore, we could not assess the relationship between medial subluxation and knee stability. However, the focus of the current study was to report this phenomenon and to suggest a simple way to measure it clinically.

This cross-sectional study may suffer from selection bias because all patients in this cohort underwent ACL reconstruction. Thus, this group of patients likely represents a subset of individuals who experienced symptoms of clinical instability and sought ACL reconstruction. The study group was not limited to those with isolated ACL rupture; however, medial subluxation still occurred in the subset of 24 patients with isolated ACL injury. This finding supports the role of the ACL in preventing the tibia from translating medially. Moreover, the cohort included in this study represents the typical spectrum of injuries occurring in the patient with ACL injury. Time between injury and examination was not known in this cohort of patients, so it potentially included those with acute injuries and those with more chronic injuries. However, no radiographic signs of OA were identified in this cohort. Furthermore, previous work revealed that the tibia subluxated laterally in osteoarthritic patients, not medially as in this ACL-deficient group.[16] This supports the assertion that our ACL-deficient cohort did not suffer from advanced OA. Our use of the most proximal aspect of the femoral notch as a reference point in our measure of tibial subluxation could be affected by arthritic changes in this region; therefore, it must be used with caution in subjects with advanced OA.

In our cadaveric model, the magnitude of axial compression (300 N) simulated about half body weight, similar to a standing radiograph. Although this was less than would be expected during walking or running, this load level was sufficient to identify increased medial translation after ACL sectioning that paralleled the clinical results. Mediolateral translations were minimal beyond this load level in a previous cadaveric model that applied up to 1600-N axial load[14]; therefore, we considered the applied load to be adequate.

In conclusion, ACL-deficient patients exhibit medial tibial subluxation and decreased varus alignment during standing radiographs. Both of these measures might be indicators of ACL injury and should be assessed after ACL reconstruction. Further study is needed to assess the long-term implications of this finding. A cadaveric model of partial weightbearing paralleled our clinical findings and could be used to assess changes in articular contact stress to better understand the biomechanical effect of the clinically observed changes in knee alignment in the frontal plane.

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