eC **A commentary by Robert F. LaPrade, MD, PhD,** is linked to the online version of this article at jbjs.org.

Tibiofemoral Kinematics During Compressive Loading of the ACL-Intact and ACL-Sectioned Knee

Roles of Tibial Slope, Medial Eminence Volume, and Anterior Laxity

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Background: Tibial geometry and knee laxity have been identified as risk factors for both noncontact anterior cruciate ligament (ACL) rupture and instability in the setting of ACL insufficiency via clinical studies; yet, their biomechanical relationships with tibiofemoral kinematics during compressive loading are less well understood. The purpose of this study was to identify the relative contributions of sagittal tibial slope, medial tibial eminence volume, and anterior knee laxity to tibiofemoral kinematics with axial compression in both ACL-intact and ACL-sectioned cadaveric knees.

Methods: Computed tomography (CT) data were collected from 13 human cadaveric knees (mean donor age, 45 ± 11 years; 8 male). Validated algorithms were used to calculate the sagittal slope of the medial and of the lateral tibial plateau as well as volume of the medial tibial eminence. Specimens were then mounted to a robotic manipulator. For both intact and ACL-sectioned conditions, the robot compressed the knee from 10 to 300 N at 15° of flexion; the net anterior tibial translation of the medial and lateral compartments and internal tibial rotation were recorded. Simple and multiple linear regressions were performed to identify correlations between kinematic outcomes and (1) osseous geometric parameters and (2) anterior laxity during a simulated Lachman test.

Results: In ACL-intact knees, anterior tibial translation of each compartment was positively correlated with the corresponding sagittal slope, and internal tibial rotation was positively correlated with the lateral sagittal slope and the sagittal slope differential ($p \leq 0.044$). In ACL-sectioned knees, anterior tibial translation of the medial compartment was positively associated with medial sagittal slope as well as a combination of medial tibial eminence volume and anterior laxity; internal tibial rotation was inversely correlated with anterior knee laxity ($p < 0.05$).

Conclusions: Under compressive loading, sagittal slope of the medial and of the lateral tibial plateau was predictive of kinematics with the ACL intact, while medial tibial eminence volume and anterior laxity were predictive of kinematics with the ACL sectioned.

Clinical Relevance: The relationships between tibial osseous morphology, anterior laxity, and knee kinematics under compression may help explain heightened risk of ACL injury and might predict knee instability after ACL rupture.

Rupture of the anterior cruciate ligament (ACL) frequently occurs in the noncontact setting during athletic activities, such as cutting or landing while axially loading the knee near full extension[1-3]. After ACL rupture, instability may expose the knee to large rotations and translations[4,5], resulting in compromised function, cartilage damage, and meniscal injury[6-9]. Previous work identified anatomical factors that increase the risk of ACL rupture and, in the setting of ACL insufficiency, cause episodes of instability and giving-way. For example, increased posterior-inferior directed slope of the lateral tibial plateau[10-15], decreased tibial eminence volume[16,17], and increased anterior laxity heighten the risk of noncontact ACL rupture[18-21]. Similarly, in the ACL-deficient knee, increased tibial slope has been associated with greater anterior tibial translation[22-27].

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Despite the importance of these anatomical factors in predicting the risk of ACL injury, their contributions to tibiofemoral kinematics in response to compressive loading is not well understood[10,19,28]. Specifically, tibiofemoral compression is known to increase both anterior tibial translation and ACL load to the point of rupture[29-31]. No studies that we are aware of, however, have linked tibial morphology and anterior laxity to kinematic variations in anterior tibial translation of both the medial and lateral tibial compartments as well as tibial rotation in the axial plane[19,24,32,33]. In addition, accounting for the slope of each tibial compartment may better predict tibiofemoral kinematics because these slopes are unrelated and may independently influence knee motions[34,35]. Finally, accounting for these additional kinematic and morphological features may help explain why patients with steep lateral tibial slope and lateral-to-medial slope asymmetry see higher rates of concomitant posterolateral meniscal root tears with ACL rupture[15].

Altogether, identifying relationships between tibiofemoral anatomy and kinematics during compressive loading would quantify the contributions of anatomical risk factors to large tibiofemoral translations and rotations, which may predispose the ACL and menisci to injury. Therefore, we used a cadaveric model to determine the relationships between tibiofemoral kinematics during compressive loading and the following anatomical and laxity features of the knee in the ACL-intact and ACL-sectioned states: (1) sagittal slope of the medial tibial plateau, (2) sagittal slope of the lateral tibial plateau, (3) volume of the medial tibial eminence, and (4) anterior knee laxity.

Materials and Methods

Computed tomography (CT) (Biograph mCT; Siemens) scans with 0.6-mm slice thickness and 0.5 × 0.5-mm in-plane pixel dimensions (settings: 140 kV, 140 mA) were obtained from 13 fresh-frozen, unpaired human cadaveric knees (mean donor age [and standard deviation], 45 ± 11 years; 8 male). Three-dimensional (3D) reconstructions of the CT data were used to measure sagittal slope of the medial and lateral tibial plateaus as well as the medial tibial eminence volume (Fig. 1)[16,36-38]. The sagittal slope measurements for the medial and lateral tibial plateaus were calculated using a previously published, validated algorithm[39], and the slope differential (lateral slope minus medial slope) was calculated because of its potential role in internal tibial rotation[38]. We isolated the volume of the anteromedial aspect of the medial tibial eminence using an objective algorithm (see Appendix)[16,25,34] adapted from the literature because this portion of the tibial eminence contacts the femoral notch in the ACL-sectioned knee[40] and, therefore, may impact tibiofemoral kinematics.

Specimens were sectioned at the midshaft of the tibial, fibular, and femoral diaphyses; all soft tissues surrounding the joint were left intact. Specimens with degeneration or abnormalities of the ligamentous, cartilaginous, meniscal, or osseous tissues were excluded. The fibula was fixed to the tibia using a carpenter screw 5 cm distal to the joint line. The tibial and femoral diaphyses were then potted in bonding cement (Bondo; 3M).

Potted specimens were then mounted to a 6-degrees-of-freedom (DOF) robot (ZX165U; Kawasaki) instrumented with a

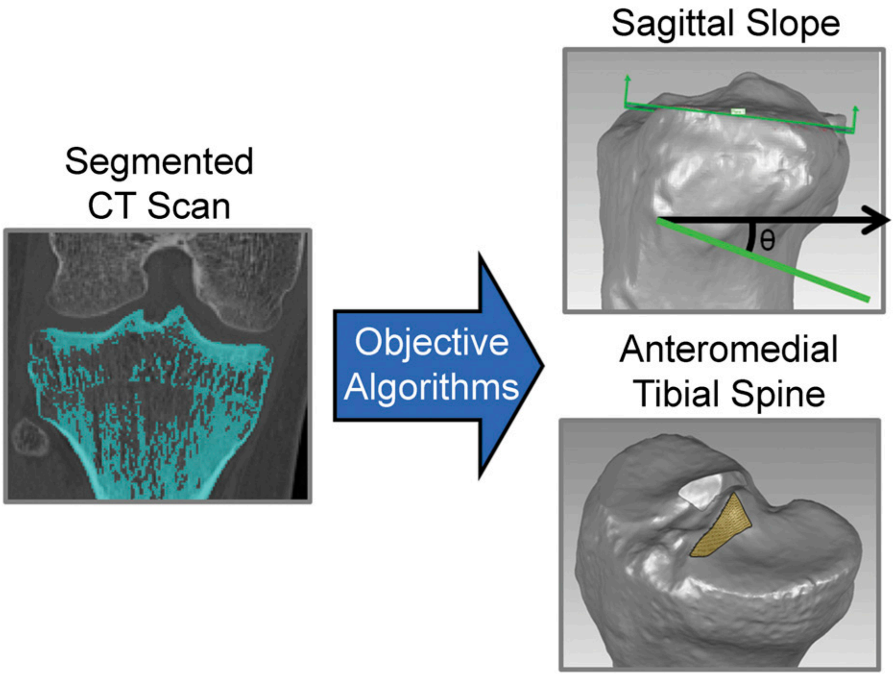

Fig. 1

Objective algorithms were used to quantify features of tibial geometry. We obtained CT scans of each knee, segmented the tibia (highlighted in light blue), and performed 3D reconstructions. Then, from the 3D reconstructions, we used objective algorithms to quantify (1) the sagittal slope of both the medial and lateral tibial plateaus (lateral plateau slope shown in green, θ) and (2) the volume of the anteromedial aspect of the medial tibial eminence (highlighted in yellow).

TABLE I Correlations Between Kinematics and Anatomical Factors in ACL-Intact Knees*

Kinematics	Anatomical Factor	β	95% CI	Adj. R^2	P Value
Medial compartment ATT	Medial sagittal slope	0.82	0.28, 1.37	0.45	0.007
	Lateral sagittal slope	−0.09	−1.25, 1.07	−0.09	0.812
	Sagittal slope differential	−0.53	−1.01, −0.05	0.29	0.033
	Medial tibial eminence volume	−0.01	−0.03, 0.01	0.07	0.194
	Anterior laxity	0.67	−1.07, 2.41	−0.02	0.426
Lateral compartment ATT	Medial sagittal slope	−0.37	−1.68, 0.94	−0.05	0.549
	Lateral sagittal slope	1.47	0.42, 2.51	0.41	0.011
	Sagittal slope differential	0.98	0.19, 1.77	0.34	0.022
	Medial tibial eminence volume	−0.01	−0.04, 0.02	−0.04	0.485
	Anterior laxity	−1.16	−4.15, 1.83	−0.02	0.416
Internal tibial rotation	Medial sagittal slope	−0.93	−2.14, 0.28	0.13	0.122
	Lateral sagittal slope	1.25	0.05, 2.45	0.26	0.044
	Sagittal slope differential	1.19	0.50, 1.88	0.53	0.003
	Medial tibial eminence volume	0.00	−0.04, 0.04	−0.09	0.969
	Anterior laxity	−1.33	−4.37, 1.71	−0.01	0.360

*ACL= anterior cruciate ligament, and ATT = anterior tibial translation.

universal force-moment sensor (Theta; ATI Industrial Automation). The femur was rigidly fixed to the ground via a pedestal, and the tibia was aligned in full extension and then mounted to a fixture attached to the end effector of the robot. Specimens were wrapped in saline solution-soaked gauze to preserve the soft tissues throughout testing[41].

After mounting the specimen to the robot, anatomical landmarks were identified using a 3D digitizer accurate to 0.32 mm (MicroScribe G2X; Solution Technologies). These landmarks included the femoral epicondyles, the distal part of the tibia approximately 25 cm distal to the joint line, the fibular insertion of the lateral collateral ligament (LCL),

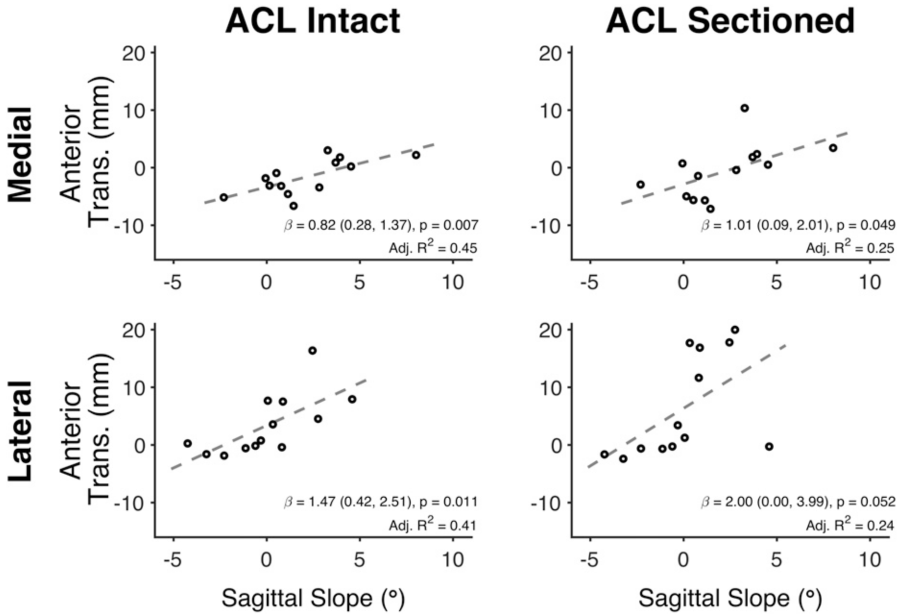

Fig. 2

Simple linear regressions relating sagittal slope of the medial and lateral tibial compartments to their respective compartmental translations (trans.). Relationships are shown for ACL-intact and ACL-sectioned knees. Kinematics reflect changes between a minimally loaded state (10 N) and 300 N compression at 15° of flexion. The 95% confidence intervals of the regression coefficients (β) are in parentheses. $P < 0.05$ is significant.

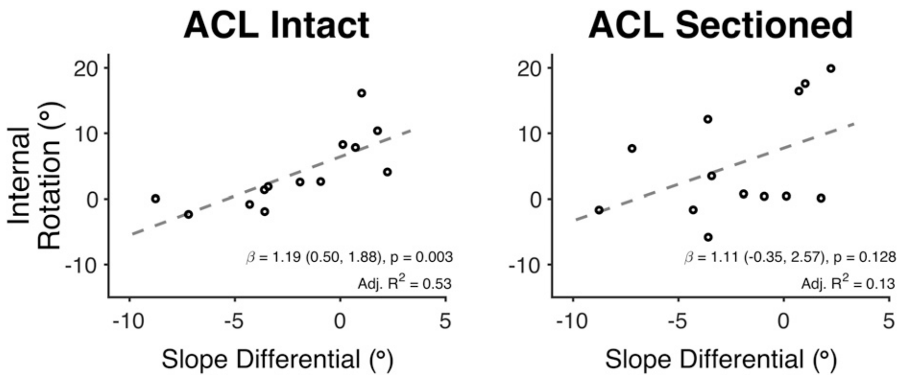

Fig. 3

Simple linear regressions relating the sagittal slope differential of the medial and lateral tibial compartments to internal tibial rotation. Relationships are shown for the ACL-intact and ACL-sectioned knees. Kinematics reflect changes between a minimally loaded state (10 N) and 300 N compression at 15° of flexion. The 95% confidence intervals of the regression coefficients (β) are in parentheses. $P < 0.05$ is significant.

and the midsubstance of the superficial medial collateral ligament (MCL) approximately 2.5 cm distal to the joint line. Using these anatomical landmarks, a knee coordinate system was defined, as previously described[42,43]. The long axis of the tibia defined internal and external rotation, the femoral epicondyles defined the flexion axis, and their common perpendicular defined the anteroposterior direction.

The knee was then flexed from 0° to 90° in 1° increments with 10 N of compression; forces and torques in the remaining directions were minimized. Algorithms were considered to have converged when resultant forces and torques differed by <5 N and <0.4 Nm, respectively, compared with the target loads[42]. To standardize the initial position for compressive loading, each knee was set to the respective posterior and external rotational extremes of its anteroposterior and internal-external rotational neutral zones[44]. Then, specimens were preconditioned with anterior and rotational loads, as previously described[42].

Axial compression was applied at 15° of flexion, an angle at which the knee experiences compressive loads during daily activities, such as walking[45]. The remaining DOF were not loaded and were left unconstrained. Compression was directed along the tibial long axis and incrementally increased from 10 to 300 N in the following steps: 10, 50, 100, 200, and 300 N. This magnitude of compression was chosen on the basis of a study by Liu-Barba et al., in which knees were compressed to 1,600 N and the greatest changes in anterior tibial translation and internal tibial rotation per unit of applied compression occurred from an unloaded state to 300 N[46]. Resulting translations and rotations were recorded with the ACL intact and after it was sectioned. Anterior tibial translations of the medial and lateral compartments were calculated by projecting the points digitized on the superficial MCL and the fibular insertion of the LCL, respectively, onto the anteroposterior axis[25].

The robot simulated a Lachman test to quantify anterior laxity for both ACL conditions[47,48]. Specifically, 134 N of anterior force was applied at the bisection of the femoral epicondyles, equivalent to 134 N of anterior force applied at the tibial tubercle, with the knee held at 30° of flexion and the remaining DOF left unconstrained; anterior tibial translation was measured using the point defined by the bisection of the femoral epicondyles[42].

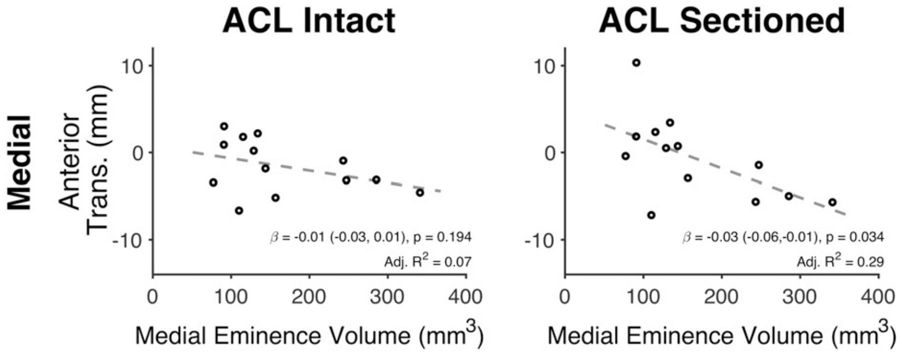

Fig. 4

Simple linear regressions relating volume of the anteromedial aspect of the medial tibial eminence to anterior translation (trans.) of the medial tibial compartment. Relationships are shown for ACL-intact and ACL-sectioned knees. Kinematics reflect changes between a minimally loaded state (10 N) and 300 N compression at 15° of flexion. The 95% confidence intervals of the regression coefficients (β) are in parentheses. $P < 0.05$ is significant.

TABLE II Correlations Between Kinematics and Anatomical Factors in ACL-Sectioned Knees*

Kinematics	Anatomical Factor	β	95% CI	Adj. R^2	P Value
Medial compartment ATT	Medial sagittal slope	1.01	0.09, 2.01	0.25	0.049
	Lateral sagittal slope	−0.25	−1.52, 1.02	−0.07	0.673
	Sagittal slope differential	−0.73	−1.56, 0.10	0.20	0.069
	Medial tibial eminence volume	−0.03	−0.06, −0.01	0.29	0.034
	Anterior laxity	0.82	−0.23, 1.87	0.14	0.117
Lateral compartment ATT	Medial sagittal slope	0.37	−1.84, 2.58	−0.08	0.726
	Lateral sagittal slope	2.00	0.00, 3.99	0.24	0.052
	Sagittal slope differential	0.81	−0.81, 2.43	0.02	0.300
	Medial tibial eminence volume	0.01	−0.06, 0.08	−0.08	0.736
	Anterior laxity	−1.83	−3.67, 0.01	0.24	0.052
Internal tibial rotation	Medial sagittal slope	−0.38	−2.49, 1.73	−0.08	0.703
	Lateral sagittal slope	1.72	−0.25, 3.69	0.18	0.086
	Sagittal slope differential	1.11	−0.35, 2.57	0.13	0.128
	Medial tibial eminence volume	0.03	−0.04, 0.10	0.03	0.260
	Anterior laxity	−1.96	−3.62, −0.30	0.32	0.026

*ACL = anterior cruciate ligament, and ATT = anterior tibial translation.

Outcome measures were the changes in anterior tibial translation and internal tibial rotation caused by increasing tibiofemoral compression from 10 to 300 N in the ACL-intact and ACL-sectioned conditions. Each outcome was summarized using means, standard deviations, and 95% confidence intervals (CIs). Simple and multiple linear regressions with stepwise selection were performed to identify correlations between the kinematic outcome measures and (1) osseous geometric parameters (sagittal slope measurements [°], slope differential [°], and medial tibial eminence volume [mm^3]) and (2) anterior laxity (mm). Regression coefficients, 95% CIs, and the adjusted coefficients of determination (adj. r^2) were reported. The normality of each measure was confirmed using Shapiro-Wilk tests ($p > 0.05$). The level of significance was set at $p < 0.05$.

Results

With the ACL intact, the mean anterior tibial translation of the medial compartment and of the lateral compartment was −1.6 ± 3.1 and 3.4 ± 5.3 mm, respectively. With the ACL sectioned, the mean anterior tibial translation of the medial and of the lateral compartment was −0.7 ± 4.8 and 6.4 ± 8.9 mm, respectively. The mean internal tibial rotation in the ACL-intact and ACL-sectioned knees was 3.9° ± 5.4° and 5.4° ± 8.5°, respectively.

In the ACL-intact condition, the sagittal slope of both compartments was correlated with tibiofemoral kinematics under applied compression (Table I). Specifically, the anterior tibial translation of each compartment in response to axial loading was correlated with the corresponding sagittal slope ($\beta = 0.82$, $p = 0.007$ for the medial compartment; and $\beta = 1.47$, $p = 0.011$ for the lateral compartment) (Fig. 2) and sagittal slope differential ($\beta = -0.53$, $p = 0.033$ for the medial compartment; and $\beta = 0.98$, $p = 0.022$ for the lateral compartment). Internal tibial rotation after axial loading was correlated with the lateral sagittal slope ($\beta = 1.25$, $p = 0.044$) and the sagittal slope differential ($\beta = 1.19$, $p = 0.003$) (Fig. 3).

In the ACL-sectioned condition, sagittal slope was less predictive of tibiofemoral kinematics under applied compression (Fig. 2). Instead, the volume of the medial tibial eminence and anterior laxity during simulated Lachman tests were more related to knee kinematics (Fig. 4, Table II). Anterior tibial translation of the medial compartment was correlated with the medial sagittal slope ($\beta = 1.01$, $p = 0.049$) (Fig. 2) and medial tibial eminence volume ($\beta = -0.03$, $p = 0.034$) (Fig. 4). Internal tibial rotation was inversely correlated with anterior laxity measured during a simulated Lachman test ($\beta = -1.96$, $p = 0.026$). Both medial tibial eminence volume and anterior laxity demonstrated correlations with anterior tibial translation of the medial compartment in a multiple linear regression model (for medial tibial eminence volume, $\beta = -0.04$ [95% CI = −0.07 to −0.01], $p = 0.004$; and for anterior laxity, $\beta = 1.02$ [95% CI = 0.29 to 1.75], $p = 0.012$).

Discussion

Risk factors for ACL injury distinctly influence tibiofemoral kinematics under compressive loading. With the ACL intact, the sagittal slope of the medial and lateral tibial plateaus was predictive of the respective anterior tibial translation of each compartment. Additionally, the lateral sagittal slope and the difference between compartments in sagittal slope primarily predicted internal tibial rotation. After sectioning the ACL, other anatomical factors emerged as predictive of tibiofemoral kinematics under compressive loading, namely, the volume of the medial tibial eminence and anterior laxity during a simulated Lachman test.

Although numerous clinical studies have shown tibial slope to be a risk factor for ACL injury[10-14,37], our study presents important biomechanical data linking greater slope to increased compartmental anterior tibial translation with compressive loads[10,21,22,37]. Since compression is known to elevate anterior tibial translation and ACL force, even to the point of failure[29-31], our findings further support the biomechanical role that greater tibial slope plays in elevating the risk of ACL injury[10,23,24,38]. By independently measuring the sagittal slope of the medial and lateral tibial plateaus, our study clarifies how lateral tibial slope and slope differential contribute to internal tibial rotation with compression when the ACL is intact. This finding supports the conjecture of Simon et al. and others[31,38,49] that increased lateral slope leads to greater lateral compartment translation and internal tibial rotation, potentially imparting higher forces on the ACL and increasing the risk of ACL injury[12,50,51]. In the current study, in ACL-intact knees, for every 1° increase in posterior-inferior directed slope, the anterior tibial translation of the lateral compartment was 1.8-times larger, on average, than that of the medial compartment (β = 1.47 mm/° for the lateral compartment, and β = 0.82 mm/° for the medial compartment) (Fig. 2). Thus, medial compartment translation during compression was less sensitive to changes in slope than the lateral compartment, likely due to medial tibial concavity, ligamentous and meniscal restraints, and the larger medial femoral condyle[34,52]. These factors constrain the medial side, facilitating pivoting of the lateral compartment around the medial compartment, leading to internal tibial rotation.

Additionally, this study demonstrated that, in ACL-intact knees, the difference in sagittal slope of the medial and lateral compartments provided a more precise prediction of internal tibial rotation than the slope of the lateral compartment alone, as indicated by the narrower CIs of the regression coefficients (Table I). Interestingly, Kolbe et al.[15] reported that, among patients with ACL injuries, those who had greater lateral slope and greater lateral-medial slope asymmetry were at greater risk for a concomitant posterolateral meniscal root tear. This finding may be explained by increased shear forces from increased internal tibial rotation. Because the tibial slope is often measured on a single projection on a lateral radiograph, the sagittal slope differential is rarely considered[53,54]. The difference between lateral and medial sagittal slope, in addition to lateral compartment slope, may be another important predictor of ACL injury and should be examined further in clinical studies.

In the ACL-sectioned state, the relationships between sagittal slope and anteroposterior compartment translations were less precise compared with those of the intact knee, as indicated by the wider CIs of the regression coefficients (Table II). Rather, the combination of medial tibial eminence volume and anterior knee laxity emerged as more predictive of tibiofemoral kinematics with compression. Specifically, a 100-mm^3 decrease of the medial eminence volume (approximately the volume of the head of a cotton swab) was predictive of a 3-to-4-mm increase in anterior tibial translation of the medial compartment. This finding suggests that contact between the tibial eminence and the femoral notch may play an important role in transmitting forces across the tibiofemoral joint; a larger medial tibial eminence may shield the ACL from injurious loads and a risk of injury[16,47]. After ACL rupture, a larger medial tibial eminence may abut the femoral notch and prevent excess anterior tibial translation[40]. This supposition is supported by radiographic observations of peaking of the medial tibial eminence and narrowing of the intercondylar notch in knees with ACL insufficiency[55-57]. Volume, however, does not reveal the specific portions of the tibial eminence that may engage the notch; a more in-depth study of the contact mechanics between the eminence and notch would further clarify the contribution of this phenomenon to knee stability. Moreover, decreased anterior laxity in the ACL-deficient knee may restrict motion of the medial compartment during axial loading[58], thereby increasing internal tibial rotation, as demonstrated in our work.

Our findings suggest that preoperative measurements of posterior tibial slopes (medial and lateral) and tibial eminence volume from magnetic resonance imaging (MRI)[16] or CT could be adapted to clinical use. It remains to be seen, however, if tibial eminence volume quantified via clinical MRI agrees with calculations from CT. Similarly, preoperative measurement of anterior laxity via a Lachman examination or KT-1000 arthrometer (MedMetric) could be adapted clinically[59]. Specifically, clinicians may use these measures to predict knee stability under compression after ACL injury and personalize treatments accordingly. For example, patients with ACL deficiency and increased posterior-inferior directed tibial slope measurements and increased slope differential, smaller medial tibial eminence volume, and increased anterior laxity may experience increased compartmental translations and internal tibial rotation, resulting in increased symptomatic instability, during weight-bearing. These increased motions may also lead to increased shear loading and damage to the cartilage and menisci[15]. Furthermore, we theorize that, after ACL reconstruction, increased tibial slope differential may subject the ACL graft to increased strain with weight-bearing. We speculate that additional measures, such as lateral extra-articular augmentation, a concurrent closing-wedge proximal tibial osteotomy, or limiting full weight-bearing in the early postoperative period, may be warranted in this subgroup of patients. In contrast, ACL-injured individuals with less posterior-inferior directed tibial slope, larger medial tibial eminence volume, and less anterior laxity may exhibit less motion and be more stable; nonoperative treatment in these patients may be an option. These suppositions, of course, require further preclinical and clinical testing.

This study had several limitations. First, we applied less compressive load than what is experienced during daily activities such as walking (>1 kN)[45,60,61]. We compressed a subset of 5 of the specimens to 600 N; translations and rotations changed minimally (<0.7 ± 0.7 mm and <0.75° ± 0.4°)

beyond 300-N compression with the ACL sectioned. With the ACL intact, continuing from 300 to 600 N yielded additional tibiofemoral motion (<2.9 ± 2.0 mm and <3.3° ± 2.4°), but the variability in kinematics among specimens at 300 N was adequate to begin to assess relationships with subchondral geometry and anterior laxity, indicating that these relationships may be elicited even with partial weight-bearing. Muscle forces, which influence kinematics[24,33,62], were excluded to isolate the effect of osseous geometry and laxity. Other anatomical characteristics (e.g., femoral osseous shapes, chondral surface morphology) that may predict weight-bearing kinematics as well as lesions that often occur concomitantly with ACL rupture (e.g., meniscal tears, other ligamentous injury) were not accounted for[28,62,63]. The same loading conditions were applied to each cadaveric knee, regardless of specimen size or donor body weight, which may have contributed to larger CIs. Since relationships emerged in this study utilizing a small sample size and without normalization of the data, additional studies with a larger sample size enabling multiple linear regression are warranted.

In conclusion, with the ACL intact, tibial sagittal slopes were predictive of tibiofemoral kinematics under compressive loading, while medial tibial eminence volume and anterior laxity emerged as predictive of kinematics with the ACL sectioned. Clinical confirmation of our findings is necessary to determine whether these relationships predict stability, function, and injury patterns after ACL rupture and whether they can be used to personalize ACL reconstruction surgery to improve outcomes.

Appendix

eA Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJS/F290). ■

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