Patellar Tendon Orientation and Strain Are Predictors of ACL Strain In Vivo During a Single-Leg Jump

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Investigation performed at Duke University, Durham, North Carolina, USA

Background: There is little in vivo data that describe the relationships between patellar tendon orientation, patellar tendon strain, and anterior cruciate ligament (ACL) strain during dynamic activities. Quantifying how the quadriceps load the ACL via the patellar tendon is important for understanding ACL injury mechanisms.

Hypothesis: We hypothesized that flexion angle, patellar tendon orientation, and patellar tendon strain influence ACL strain during a single-leg jump. Specifically, we hypothesized that patellar tendon and ACL strains would increase concurrently when the knee is positioned near extension during the jump.

Study Design: Descriptive laboratory study.

Methods: Models of the femur, tibia, ACL, patellar tendon, and quadriceps tendon attachment sites of 8 male participants were generated from magnetic resonance imaging (MRI). High-speed biplanar radiographs during a single-leg jump were obtained. The bone models were registered to the radiographs, thereby reproducing the in vivo positions of the bones, ligament, and tendon attachment sites. Flexion angle, patellar tendon orientation, patellar tendon strain, and ACL strain were measured from the registered models. ACL and patellar tendon strains were approximated by normalizing their length at each knee position to their length at the time of MRI. Two separate bivariate linear regression models were used to assess relationships between flexion angle and patellar tendon orientation and between ACL strain and patellar tendon strain. A multivariate linear regression model was used to assess whether flexion angle and patellar tendon strain were significant predictors of ACL strain during the inflight and landing portions of the jump.

Results: Both flexion angle and patellar tendon strain were significant predictors ($P < .05$) of ACL strain. These results indicate that elevated ACL and patellar tendon strains were observed concurrently when the knee was positioned near extension.

Conclusion: Concurrent increases in patellar tendon and ACL strains indicate that the quadriceps load the ACL via the patellar tendon when the knee is positioned near extension.

Clinical Relevance: Increased ACL strain when the knee is positioned near extension before landing may be due to quadriceps contraction. Thus, landing with unanticipated timing on an extended knee may increase vulnerability to ACL injury as a taut ligament is more likely to fail.

Keywords: biplanar radiography; magnetic resonance imaging; anterior cruciate ligament; flexion angle; quadriceps; imaging

Despite its critical role in the flexion/extension mechanism of the knee joint, there is little in vivo data to describe patellar tendon orientation and strain during dynamic activities or athletic maneuvers.[13,21,41] Such data are particularly important given that a primary role of the patellar tendon is to transmit forces originating from the quadriceps muscle to the tibia.[48] Specifically, the patellar tendon is positioned to increase the relative contribution of the anterior shear component of quadriceps force acting on the tibia when the knee is positioned at low flexion angles as well as the relative contribution of posterior shear force when the knee is flexed (Figure 1).[13,21,41]

Furthermore, as the anterior cruciate ligament (ACL) is a primary restraint of anterior displacement of the tibia relative to the femur, increased anterior shear on the tibia can result in ACL strain.[7] To this point, studies have shown that anterior tibial translation and ACL strain result from simulated quadriceps activation when the knee is extended.[2,15-17,31] Additionally, isometric quadriceps contraction produces ACL strain in vivo when the knee is positioned at low flexion angles.[4] Importantly, ACL strain is a critical parameter for understanding its propensity for failure, as a taut ligament may have a greater likelihood of rupture.[8,29] Therefore, in vivo data

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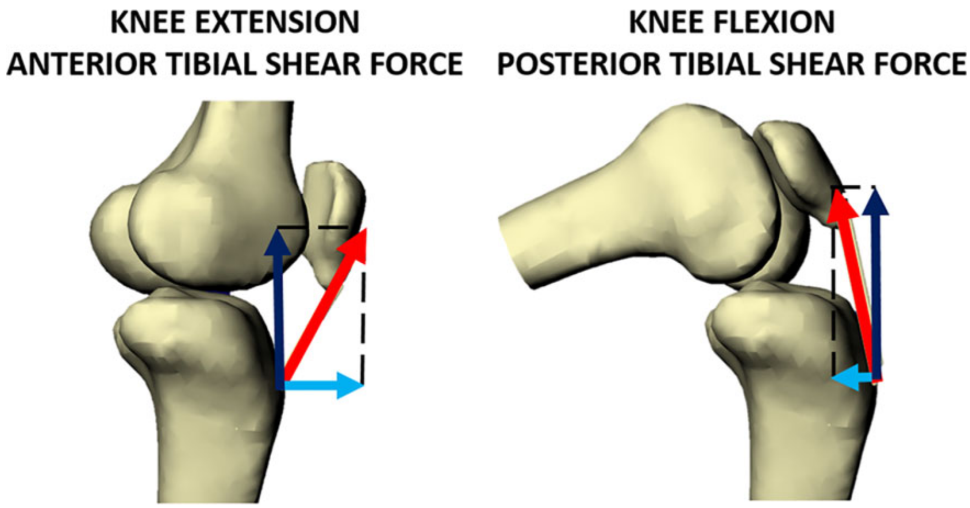

Figure 1. The patellar tendon is oriented to increase the relative contribution of the anterior shear component of quadriceps force acting on the tibia when the knee is positioned at low flexion angles. At greater knee flexion angles, the shear component is directed posteriorly. The red arrows represent force acting along the patellar tendon. The light blue arrows represent the shear component of this force. Adapted from DeFrate et al[13] with permission.

describing the relationships between patellar tendon strain, patellar tendon orientation, and ACL strain during dynamic activity will provide insight into knee positions, motions, and muscle activation patterns that increase the vulnerability of the ACL to rupture.[5,15] These findings may also be important for the design of post-ACL reconstruction (ACLR) rehabilitation protocols and injury-prevention programs.[4,25]

Knee joint kinematics and ligament deformations have been measured in vivo using biplanar radiography integrated with 3-dimensional (3-D) models of the knee joint created from magnetic resonance imaging (MRI).[14,20,23,36,51] These joint models may consist of the femur, tibia, and associated ligament or tendon attachment site footprints. By registering the bone models to the biplanar radiographs, the 3-D positions of the bones at the time of radiographic imaging can be reproduced.[37,51,52] Ligament elongation and strain can then be quantified by measuring the distances between the attachment site footprints for each knee position.[13,36,37,51] Using these techniques, a previous study from our lab investigated the relationships between ACL length, knee flexion angle, and patellar tendon orientation for various knee positions using static biplanar radiography.[21] Recently, we developed a technique to register MRI-based bone models to high-speed biplanar radiographs, which has been used to measure dynamic ACL elongation and strain.[19,22,23] This technique can also be applied to study in vivo patellar motion as well as the elongation of the patellar tendon during dynamic activities.

Thus, the objective of the present study was to expand on this previously developed method[23] to measure in vivo patellar tendon strain and orientation in addition to knee kinematics and ACL strain during the inflight and landing portions of a single-leg jump.[19] We hypothesized that patellar tendon strain, patellar tendon orientation, and knee flexion angle would influence ACL strain during the jump.[13,21] Specifically, we hypothesized that patellar tendon strain, which may be indicative of quadriceps contraction, as well as ACL strain would increase concurrently when the knee was positioned in extension. Furthermore, we expected to observe increased ACL strain concurrent with increased patellar tendon strain before initial ground contact.[19] This information may provide insight into how noncontact ACL ruptures may occur during a jump landing.

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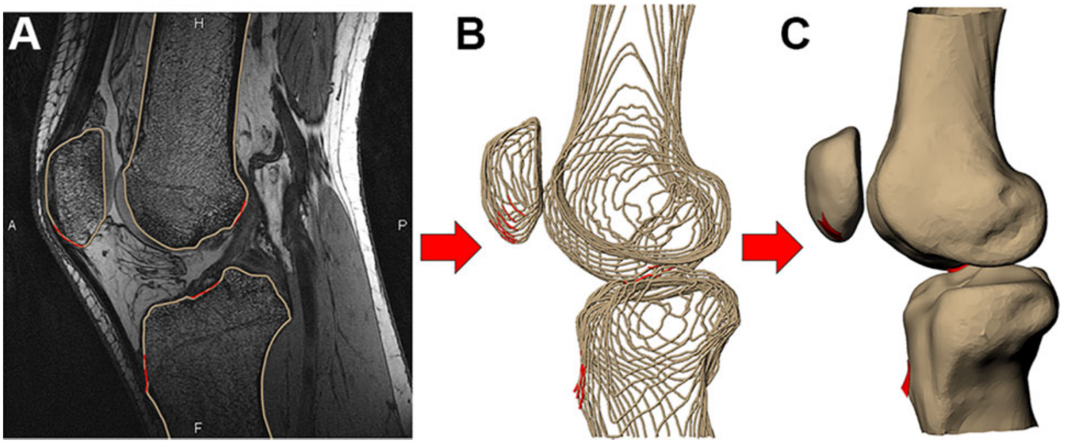

Figure 2. Models of the knee joint were created from magnetic resonance imaging (MRI). (A) Outer margins of the femur, tibia, patella, and patellar tendon and anterior cruciate ligament (ACL) attachment sites were outlined on the MRI. Attachment sites of the ACL and patellar tendon are shown in red. (B) The contours were compiled into wireframe models. (C) Three-dimensional mesh models were created from the wireframe models. Image reproduced from Englander et al[21] with permission.

METHODS

Eight asymptomatic male participants (mean ± SD age, 28.4 ± 4.5 years; body mass index, 24.8 ± 2.3 kg/m^2) with no history of lower-extremity injury or surgery were evaluated using a protocol approved by the institutional review board. The sample size for this study was based on a prior in vivo imaging study that measured ACL strain during a bilateral jumping motion using a combination of motion capture and imaging techniques.[50] The right knee of each participant was imaged using a 3-T MRI scanner (Trio Tim; Siemens Medical Solutions USA). Sagittal, coronal, and axial images were acquired while participants lay supine, using a double-echo, steady-state sequence and an 8-channel knee coil (resolution, 0.3 × 0.3 × 1 mm; flip angle, 25°; repetition time, 17 ms; echo time, 6 ms).[42] Outlines of the femur, tibia, and patella as well as the attachment site footprints of the patellar tendon and ACL were segmented manually from the sagittal plane images using solid-modeling software (Rhinoceros 4.0; Robert McNeel and Associates) (Figure 2). The attachment site footprints of the ACL were also segmented in the coronal plane. These segmentations were compiled into 3-D models of the joint (Geomagic). This modeling procedure has been described in previous studies.[11,34,36,43,44] The positions and shapes of the ACL and patellar tendon attachment sites were confirmed in the 3 orthogonal imaging planes. Prior validation studies have demonstrated that this approach can locate the center of the ACL footprint to within 0.3 ± 0.2 mm.[1,49]

After MRI, the participants were imaged using a high-speed biplanar radiography system with a frame rate of 120 Hz and a pulse width of 1.5 milliseconds, as previously described.[19,22,23] Each radiograph had a resolution of 1152 × 1152 pixels. First, the positions of the sources and intensifiers were adjusted to ensure that the jumping motion could be captured in the field of view without the contralateral leg's obscuring the joint of interest. Next, calibration images were acquired to re-create the geometry of the imaging setup and correct for image distortion, as previously described.[23]

Participants stood on a dual belt–instrumented treadmill (Bertec) that was used to record ground reaction forces at a sampling rate of 1200 Hz. Each individual was then instructed to perform a single-leg jumping motion.[19] The data were inspected to ensure that none of the bones extended entirely outside of the field of view of the imaging system, although the trial was considered valid if either the femur or tibia extended partially outside of the field of view.[23] Each in vivo experiment used a radiographic protocol not exceeding 110 kVp/200 mA. To assess radiation risk to participants, the radiation effective dose (a weighted mean of absorbed doses to bone surfaces, skin, and soft tissues) was calculated from the total skin entrance exposure and energy absorption by the tissues. The total effective dose was less than 0.14 mSv per participant, which is considerably less than the annual natural background radiation in the United States (range, 2.4-3.1 mSv).[6,38,40]

After data collection, the 3-D bone models, calibration images, and biplanar radiographs were imported into custom registration software.[23] The software was employed to move each bone separately within 6 degrees of freedom until its projection onto the 2 imaging planes from the perspective of the radiographic sources matched the outline of bones as seen in the radiographs (Figure 3). Previous validation of this technique has been shown to have a precision of approximately 70 microns in measuring the relative distances between 2 matched bones.[23]

After reproducing the in vivo positions of the bones during the jump (Figure 4), knee flexion angle, patellar tendon orientation, and the length of the ACL and patellar tendon were measured using a standardized anatomic coordinate system (Figure 5).[20,28,51] The flexion angle was measured about the femoral transepicondylar axis and defined as the angle between the long axis of the femur and the long axis of the tibia. Zero degrees of knee flexion is indicative of a straight knee, and increasingly positive angles are

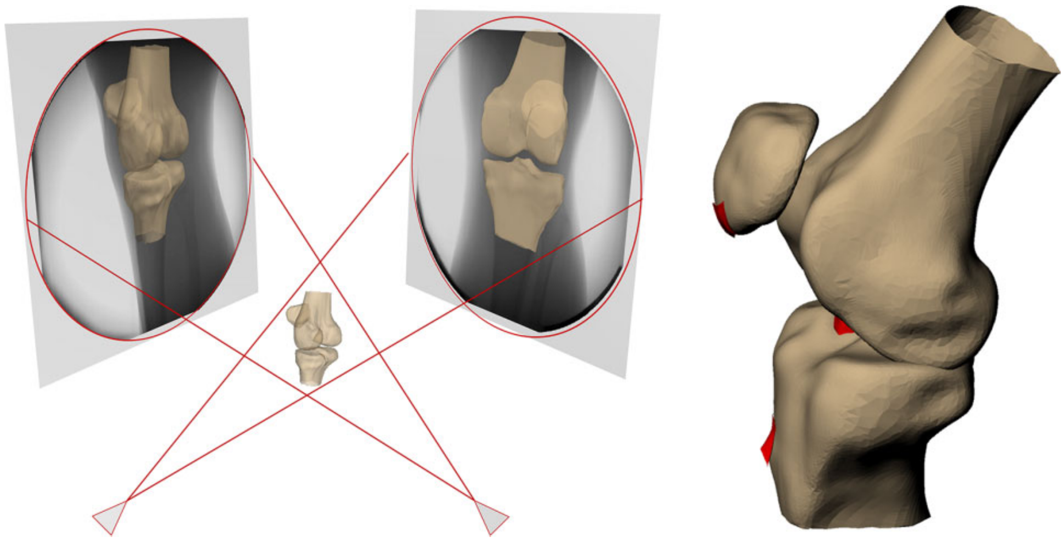

Figure 3. To reproduce the positions of the knee joint during the single-leg jump, each bone was moved separately within 6 degrees of freedom until its projections onto the 2 imaging planes from the perspective of the radiographic sources matched the bones as seen in the radiographs. Previous validation of this technique has been shown to have a precision of approximately 70 μm in measuring the relative distances between 2 matched bones. Image reproduced from Englander et al[21] with permission. Red patches denote the positions of the patellar tendon and ACL attachment sites.

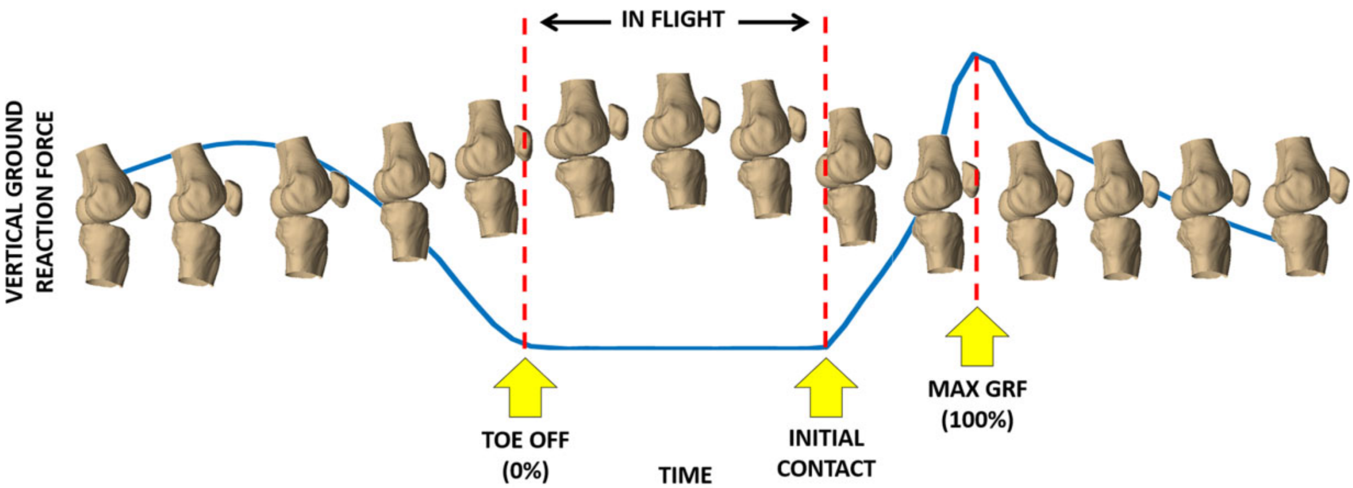

Figure 4. The in vivo positions of the tibia, femur, and patella were reproduced during the single-leg jump (example of single participant). Using the ground reaction forces (GRF), toe-off (designated as 0% of the jump) and the point of maximum GRF (designated as 100% of the jump) were identified. These timepoints were used to normalize the data to enable comparison across participants.

indicative of increasing knee flexion. Patellar tendon orientation represents the angle between the long axis of the tibia and the line of action of the patellar tendon (represented by a line connecting the centroid of its attachment site footprints on the patella and tibia) measured in the sagittal plane (Figure 5B).[21] Positive angles indicate that the patellar tendon attachment site on the patella is oriented anterior to its attachment site on the tibia.[41] ACL[37] and patellar tendon lengths[13,21] were measured as the centroid to centroid distance between their attachment site footprints. Strain was approximated as the length of the ligament or tendon in each knee position during the dynamic activity normalized to its length during MRI, when it is likely to be minimally loaded.[26,49]

Important timepoints during the jump were identified using the vertical component of the ground reaction force obtained from the force plates. Specifically, the jump toe-off (designated as 0% of the jump) was defined as the last point where force registered on the force plate before the jump toe-off. One hundred percent of the jump was defined as the point where maximum ground reaction force was reached after landing (Figure 4). All measurements were interpolated from

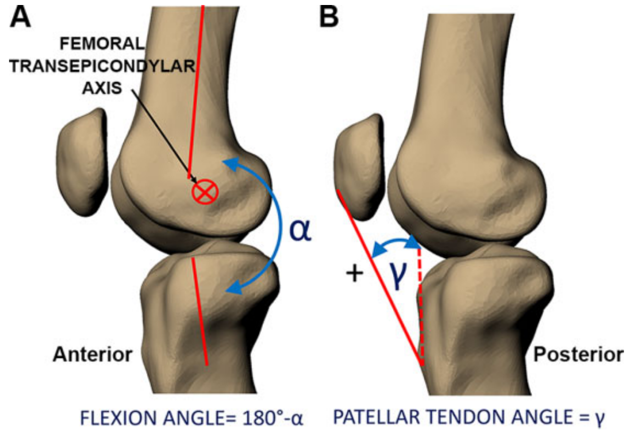

Figure 5. Knee joint angles were determined using a standardized coordinate system based on bone anatomy. (A) Flexion angle represents the angle between the long axes of the femur and tibia about the femoral transepicondylar axis. (B) Patellar tendon orientation represents the angle between the long axis of the tibia and the line of action of the patellar tendon (represented by a line connecting the centroids of its attachment site footprints on the patella and tibia) measured in the sagittal plane. Image adapted from Englander et al[21] with permission.

the data to represent values of each variable as a function of percentage jump in 5% increments. This normalization procedure was done in order to allow for comparison of data across participants. Based on the results from previous studies,[19,50] timepoints of interest in this study spanned between 35% and 100% of the jump, which consisted of the inflight, initial contact, and landing portions of the jump.

Statistical Analysis

Statistical analysis was performed using Matlab (Version R2016B; Mathworks). Using the Anderson-Darling test, there was no evidence that nonparametric statistics would be required for these analyses. First, a bivariate linear regression was performed to assess the relationship between ACL strain and patellar tendon strain for time points between 35% and 100% of the jump. In a second analysis, a bivariate linear regression was performed to assess the relationship between flexion angle and patellar tendon orientation for time points between 35% and 100% of the jump. Third, a multivariate linear regression model was used to determine whether knee flexion angle and patellar tendon strain were significant predictors of ACL strain during the inflight and landing portions of the jump. In this analysis, patellar tendon orientation was not included as an independent variable due to the strong relationship between flexion angle and patellar tendon orientation that was revealed in the bivariate regression of these 2 variables. This served to avoid collinearity between predictor variables within the same model. Importantly, we chose to include flexion angle rather than patellar tendon angle in the multivariate model because flexion is modifiable during activity and may therefore be relevant to injury prevention. Furthermore, a robust variance estimator was added to the multivariate regression model to account for the potential correlation between timepoints within participants and to avoid incorrect assumptions with model specification when estimating the variance. Statistical significance was defined as $P < .05$ for all analyses.

RESULTS

The mean ACL length measured at the time of MRI was 26.6 ± 4.0 mm (mean ± SD across participants). The mean patellar tendon length measured at the time of MRI was 58.5 ± 4.0 mm. These participant-specific resting lengths at the time of MRI were used in ACL and patellar tendon strain calculations for each individual. The mean patellar tendon orientation at the time of MRI was 22° ± 5°. Elevated patellar tendon strain (7% ± 3%) was observed concurrently with a maximum in ACL strain (7% ± 4%) at 40% of the jump (61 ± 42 ms before initial ground contact). These peaks in ACL strain and patellar tendon strain were statistically different from zero with $P < .01$ (single mean t test). At this point, the participants were not in contact with the ground, and they were positioned with their knees extended at a mean flexion angle of –2° ± 8° and a mean patellar tendon orientation of 18° ± 6°.

A bivariate linear regression revealed that mean flexion angle was inversely related to mean patellar tendon orientation ($r^2 = 0.95$; $P = 3.4 \times 10^{-9}$). This result indicates that patellar tendon angle (related to the relative magnitude of the anterior component of shear force acting via the patellar tendon) increases with knee extension during the jump (Figure 6A). Additionally, a second bivariate linear regression revealed that mean ACL strain is related to patellar tendon strain during the inflight and landing portions of the jump ($r^2 = 0.65$; $P = 4.8 \times 10^{-4}$) (Figure 6B). However, we hypothesized that additional factors, such as flexion angle, may also influence the relationship between patellar tendon strain and ACL strain.

In support of this hypothesis, multivariate linear regression revealed that both knee flexion angle and patellar tendon strain were significant predictors ($P < .05$) of ACL strain during the jump. The multivariate linear regression results are summarized in Table 1.

Together, the results of these analyses suggest that the effect of quadriceps contraction, acting via the patellar tendon, on ACL strain depends on the knee flexion angle and orientation of the patellar tendon. Specifically, as the knee is extended, the patellar tendon angle increases, resulting in a larger anterior shear component of quadriceps force acting on the tibia and a larger ACL strain.

DISCUSSION

The present study quantified relationships between in vivo ACL strain, knee flexion angle, patellar tendon strain, and patellar tendon orientation during the inflight and landing

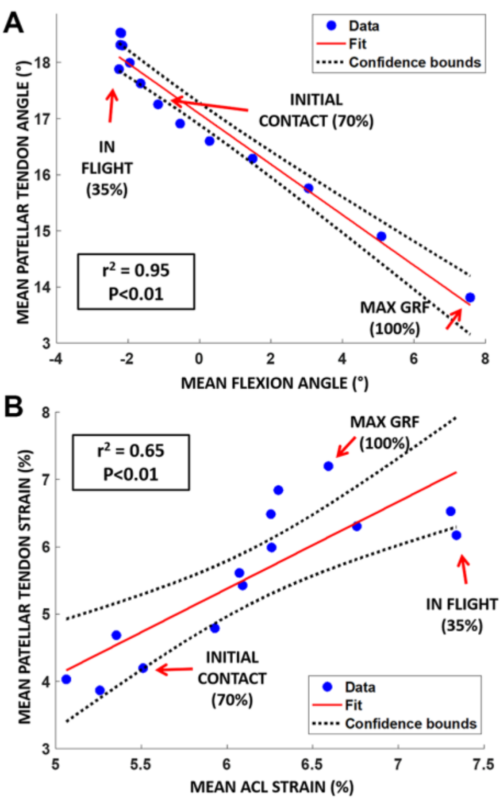

Figure 6. Data points represent the mean across participants for each percentage of the jump. The red line represents the bivariate linear regression fit to the data, and the dashed lines represent the 95% CIs of the regression. (A) A bivariate linear regression revealed that mean flexion angle was inversely related to mean patellar tendon angle ($r^2 = 0.95$; $P = 3.4 \times 10^{-9}$), indicating that the patellar tendon angle (related to the relative magnitude of the anterior component of shear force acting via the patellar tendon) increases with knee extension during the jump. (B) A bivariate linear regression revealed that mean anterior cruciate ligament (ACL) strain was positively related to patellar tendon strain during the jump ($r^2 = 0.65$; $P = 4.8 \times 10^{-4}$). GRF, ground reaction force.

TABLE 1
Predictors of Anterior Cruciate Ligament Strain During a Single-Leg Jump

	Estimate	SE	*t* Statistic	*P* Value
Intercept	0.9	1.0	0.9	.34
Flexion angle, deg	–0.2	0.2	–3.4	.0008
Patellar tendon strain, %	0.9	0.1	5.9	<.0001

portions of a single-leg jump. During these motions, flexion angle was highly predictive of patellar tendon orientation, and patellar tendon strain was highly predictive of ACL strain. Additionally, in a multivariate regression model incorporating flexion angle and patellar tendon strain, both were significant predictors of ACL strain. Notably, increased patellar tendon strain and ACL strain were observed concurrently before ground contact with the knee positioned near extension.

The finding of increased patellar tendon strain before landing suggests that quadriceps activation occurs during this portion of the jump, potentially in anticipation of landing.[18,35] This assertion is supported by previous literature.[9,18,35] Specifically, an increase in quadriceps electromyography activity has been observed approximately 50 milliseconds before landing during a stop jump task,[9] suggesting that the quadriceps are activated in anticipation of ground impact. Importantly, this pattern of prelanding quadriceps activation[18,35] has been demonstrated in other jumping activities. As the patellar tendon is connected in series with the quadriceps muscle, muscle activation can elicit patellar tendon strain. However, future studies should further investigate the timing and magnitude of quadriceps activation during single-leg jumping.

Furthermore, the results of this study indicate that the influence of patellar tendon strain on ACL strain is moderated by the orientation of the patellar tendon. Specifically, when the knee is positioned near extension, and the patellar tendon angle is relatively large, there is a relative increase in the magnitude of the anterior shear component of the quadriceps force acting on the tibia (Figure 1).[13,41] As a primary function of the ACL is to resist anterior tibial translation,[7] an increase in the anterior shear component of quadriceps force acting via the patellar tendon increases loading on the ACL. In support of this hypothesis, there have been several studies demonstrating increased ACL strain with the knee near extension using simulated quadriceps contraction[15-17] and with isometric quadriceps contraction measured in vivo using strain transducers.[3,4] Thus, these data may provide important insight into why landing in extension represents increased risk of ACL failure. Specifically, elevated quadriceps activity may load the ACL when the knee is extended before contact with the ground during a normal single-leg landing.[15] This may indicate that the ACL is vulnerable to injury in this scenario, particularly in the presence of a movement perturbation or change in landing strategy with unanticipated timing.

Importantly, the multivariate linear regression analysis indicated that ACL strain was significantly influenced by both flexion angle and patellar tendon strain. This result suggests that the effect of quadriceps activation via the patellar tendon on ACL strain is influenced by the position of the knee. Specifically, the significant inverse relationship between flexion angle and patellar tendon orientation indicates that increased knee flexion would decrease the patellar tendon angle and therefore the relative magnitude of the anterior shear force acting on the tibia during the jump.[13] Therefore, these results support the assertion that increased knee flexion during landing may reduce the effect of quadriceps loading on ACL strain. Future studies should further investigate this hypothesis by measuring ACL and patellar tendon strain during different (flexed vs stiff) landing strategies.

The results of this study may be important to consider in the context of the long-term outcomes of ACLR. Bone-patellar tendon-bone (BTB),[30] quadriceps tendon,[39] and hamstring tendon[12,27] autografts are commonly used in ACLR. Interestingly, a recent study found that the odds of a recurrent ACL graft revision on the ipsilateral knee for patients receiving a hamstring autograft were 2.1 times those of a patient receiving a BTB autograft.[33] It is possible that harvesting the graft influences the mechanisms by which strain is induced in the ACL via the patellar tendon, potentially affecting mechanisms of graft failure. However, it remains unclear how harvesting portions of the extensor mechanism[46,47] from the quadriceps and patellar tendon may affect patellar tendon strain as well as transmission of forces to the ACL graft. Furthermore, quadriceps weakness appears to be a very common strength deficit after reconstruction, regardless of graft type.[32] Future work should investigate the effect of various reconstruction strategies on patellar tendon and ACL graft strains.

The vertical single-leg jump activity was chosen for this study because we aimed to measure in vivo ACL and patellar tendon deformation patterns during the inflight and landing portions of the jump.[19] This required that the motion be contained within the field of view of the biplanar radiography system. However, future investigations using this technique may examine larger movements by focusing on the period of time just before landing during other relevant dynamic movements, such as anticipated or unanticipated cutting or elevated box jump landings. Additionally, data from a single trial for each individual were included in these analyses, which minimized radiation exposure for each participant. However, the kinematics of each of the jumps did remain consistent across individuals. In addition, the present study focused on only male participants. Prior studies have shown differences in kinematic landing patterns between male and female participants,[10] and controversy remains in the literature regarding differences in the mechanisms by which males and females sustain ACL injuries.[44,45] Thus, future investigations may compare ACL strain patterns during jump landings between male and female participants. Additional future studies may include comparing ACL and patellar tendon strain patterns between different landing strategies or may incorporate EMG measurements to further probe the involvement of quadriceps activation.

Furthermore, it is important to note that ligament and tendon strains in this study were approximated by normalizing their lengths to a reference length, defined as the length measured in a relaxed and extended position during MRI. However, it is difficult to precisely measure the true unloaded length of a ligament or tendon in vivo.[22,24,26] Therefore, although there remains some uncertainty in the unloaded length when estimating strain in this way, peaks in the estimated and true strains should occur concurrently, and the relationships between variables described in this study will not be affected. Therefore, potential uncertainty in reference lengths should not affect the overall conclusions of this study.

CONCLUSION

This study's findings provide important insight into why landing with the knee in extension can increase the risk of ACL injury. Specifically, these data suggest that when landing on an extended knee, quadriceps activation in preparation for landing (reflected by increased patellar tendon strain) leads to tension in the ACL due to the orientation of the patellar tendon at low flexion angles. Elevated ACL tension may increase the likelihood of failure in the case of a landing with unanticipated timing.

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