Tibiofemoral Alignment: Contributing Factors to Noncontact Anterior Cruciate Ligament Injury

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Background: The mechanisms of noncontact anterior cruciate ligament injury remain undefined. The purpose of this study was to identify the tibiofemoral alignment in the lateral compartment of the knee for three variations of a one-limb landing in noncontact sports activities: the safe, provocative, and exaggerated provocative positions. These positions were chosen on the basis of a previous study that measured the average joint angles of the limb at the point of ground contact for athletes who landed without injury (safe) and those who sustained an anterior cruciate ligament injury (provocative). It was hypothesized that, in the provocative positions, altered tibiofemoral alignment predisposes the knee to possible subluxation, potentially leading to an anterior cruciate ligament injury.

Methods: Magnetic resonance images were acquired for a single knee in twenty-five noninjured athletes for the three landing positions. The angle between the posterior tibial slope and the femur along with three distances (from the tibiofemoral point of contact to [1] the femoral sulcus point, [2] the posterior tibial point, and [3] the most anterior point of the circular posterior aspect of the condyle) were measured for each acquisition.

Results: The tibial slope relative to the femur was directed significantly more inferior to superior in the provocative and exaggerated positions than in the safe landing position. Similarly, as the limb transitioned from the safe to the provocative positions, the tibiofemoral joint contact point was significantly closer to the femoral sulcus point and to the most anterior point of the circular posterior portion of the lateral femoral condyle.

Conclusions: As the limb moves toward the provocative landing position, the anatomical alignment based on slope and contact characteristics places the knee at possible risk for noncontact anterior cruciate ligament injury. An enhanced understanding of the mechanism of anterior cruciate ligament injury may lead to improved preventative strategies.

Despite intense study of the anterior cruciate ligament injury during the past three decades, the mechanisms of noncontact injury, which are responsible for approximately 70% of all anterior cruciate ligament injuries, have not been clearly defined[1]. Theories have proposed various contributors to or risk factors for injury: intrinsic[1-4] and extrinsic[1,4-6] entities; the antagonist-agonist relationships[7,8]; quadriceps contraction[4]; and, more recently, axial compressive forces on the lateral aspect of the joint[9-12].

Initial reports on mechanisms of anterior cruciate ligament injury were based on interviews with the athletes or descriptive analyses of videotapes[1,5,13]. A recent study of the one-limb landing positions associated with anterior cruciate ligament injury and noninjury found that injury occurred when the foot was less plantar flexed and the hip was more flexed during landing[11]. On the basis of these findings, so-called safe and provocative landing positions were defined and the average hip, knee, and ankle angles at initial ground contact were determined from videotapes of athletes during noncontact one-limb landings. Because the safe and provocative positions were based on average joint angles, a third position at the extreme of the provocative range was chosen. Compared with the provocative position, the exaggerated provocative position further increased hip flexion and knee extension.

Because most noncontact anterior cruciate ligament injuries are associated with bone bruises on the posterolateral

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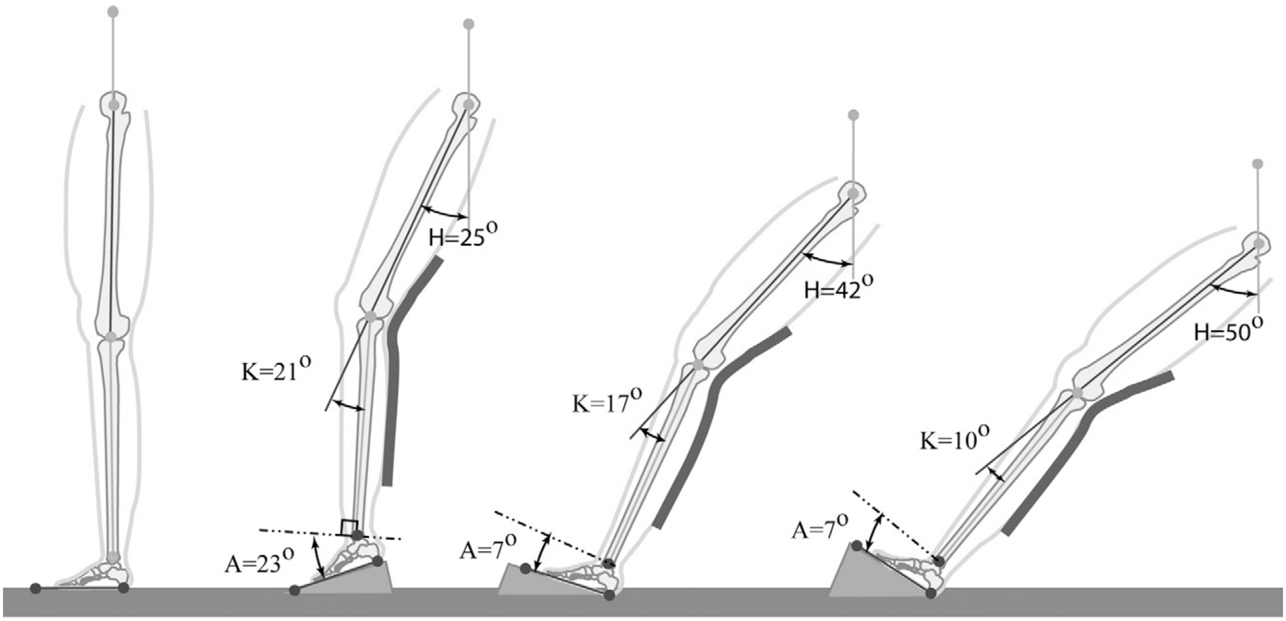

Fig. 1

This diagram shows a limb in the anatomically neutral position and in the three study positions: safe, provocative, and exaggerated provocative. Compared with the safe position, the positions of potential injury of the anterior cruciate ligament (provocative and exaggerated provocative) were associated with less plantar flexion of the ankle (A), greater extension of the knee (K), and greater flexion of the hip (H). The dark gray line behind the knee represents the splint used to maintain the proper knee angle. A rigid wedge (triangle below the foot) was used to position the ankle.

aspect of the tibial plateau and the sulcus of the lateral femoral condyle[14,15], it is likely that, during injury, there is an anterior and internal tibial shift, with the lateral aspect of the tibia shifting forward relative to the femur. Therefore, the purpose of this study was to quantify the tibiofemoral alignment in the lateral compartment of the knee for three variations of a one-limb landing in noncontact sports activity: the safe, provocative, and exaggerated provocative positions. It was hypothesized that, in a provocative position, altered tibiofemoral alignment predisposes the knee to a possible gravitational subluxation, potentially exposing it to an anterior cruciate ligament injury. There were three subhypotheses: (1) the tibial slope relative to the femur is directed more inferior to superior (more vertical) in the provocative positions than in the safe position; (2) the point of contact (or the midpoint of the line of contact between the femur and the tibia) is closer to the sulcus on the lateral femoral condyle in the provocative positions than in the safe position, increasing the probability of a pivot shift; and (3) the lateral femoral condyle contacts the tibial plateau on its flatter anterior surface in the provocative positions rather than on the rounder posterior surface contacted in the safe position.

Materials and Methods

This study received institutional review board approval and was registered at ClinicalTrials.gov (NCT00855023).

Study Population

We recruited healthy volunteer athletes and excluded those who had any of the following criteria: (1) contraindications to magnetic resonance imaging (such as pregnancy or implanted hardware); (2) relevant medical problems (such as connective tissue problems, paralyzed hemidiaphragm, morbid obesity, or claustrophobia); (3) clinical signs of an impairment or abnormality in the knee (such as abnormal range of motion, muscle weakness, or malalignment); (4) injury to the knee that required medical attention; (5) previous surgery on the knee; or (6) current pain in the knee.

The twenty-five athletes who had none of the exclusion criteria and who provided signed consent formed the study group. The mean age of the twelve men and thirteen women was twenty-five years (range, eighteen to forty-five years). One limb (randomized with regard to right or left) of each participant was designated for positioning, imaging, and measuring.

Positions, Imaging, and Measurements

On the basis of a previous study relating landing position to injury of the anterior cruciate ligament[11], three positions were selected for assessment: one associated with no injury (safe position), one associated with anterior cruciate ligament injury (provocative), and one position that exaggerated the anterior cruciate ligament injury position (exaggerated provocative)

Fig. 2

Photograph of a subject in the safe position for a magnetic resonance imaging scan. The subject is standing with partial weight support provided by a small seat, a posterior fiberglass splint to support the knee, and a firm wedge under the foot to maintain ankle position.

(Fig. 1). For the safe position, the subject was positioned with the hip flexed 25°, the knee flexed 21°, and the ankle at 23° of plantar flexion. In the provocative position, the subject was positioned with the hip flexed 42°, the knee flexed 17°, and the ankle at 7° of plantar flexion. In the exaggerated provocative position, the subject was positioned with the hip flexed 50°, the knee flexed 10°, and the ankle at 7° of plantar flexion. For all positions, hip abduction was set at shoulder width and tibial rotation was set at neutral (0°).

Joint angles were measured with a goniometer, and the limb was supported with a specialized posterior fiberglass splint compatible with the magnetic resonance imaging scanner and preset at the correct knee angle (Fig. 2). The foot was secured on a firm foam positioning device to obtain the correct ankle angle. Although athletes in the safe position landed with forefoot contact on the ground, this wedge was used under the foot to replicate the ankle angle because subjects were unable to hold the forefoot position during the magnetic resonance imaging scan. In the sagittal plane, the ankle joint was measured as the angle between the axis of the lower limb and the plantar surface of the shoe[11,16]. The knee flexion angle was measured as the angle between a line connecting the superior tip of the greater trochanter to the midpoint of the lateral aspect of the knee at the joint line and a line connecting the midpoint of the lateral aspect of the knee at the joint line to the anterior point of the distal tip of the fibula. The hip angle was measured as the angle between the line from the superior tip of the acromioclavicular joint to the superior tip of the greater trochanter and the line from the superior tip of the greater trochanter to the midpoint of the lateral aspect of the knee at the joint line[17]. Neutral tibial rotation was achieved by placing the subject's patella and foot perpendicular to the plane of the body and the end of the foot platform.

For all three limb positions, each subject was placed in a standing position with partial weight support, provided by a small seat integral with the magnetic resonance imaging spine

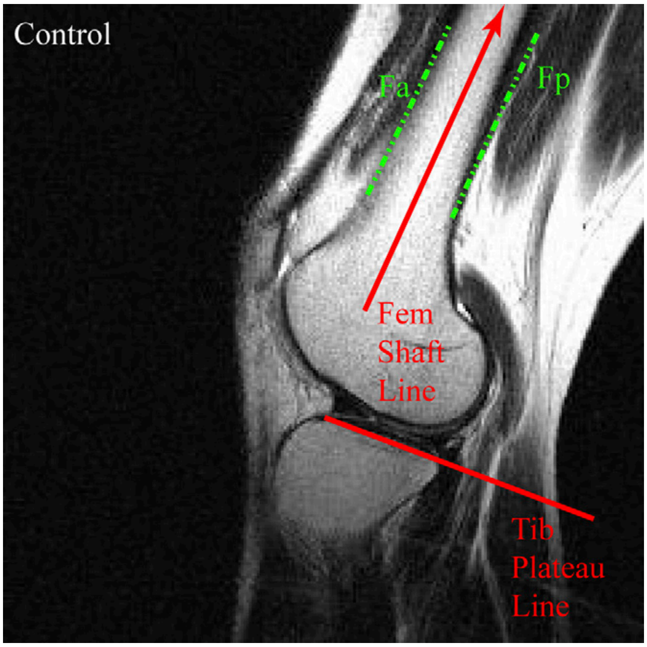

Fig. 3-A

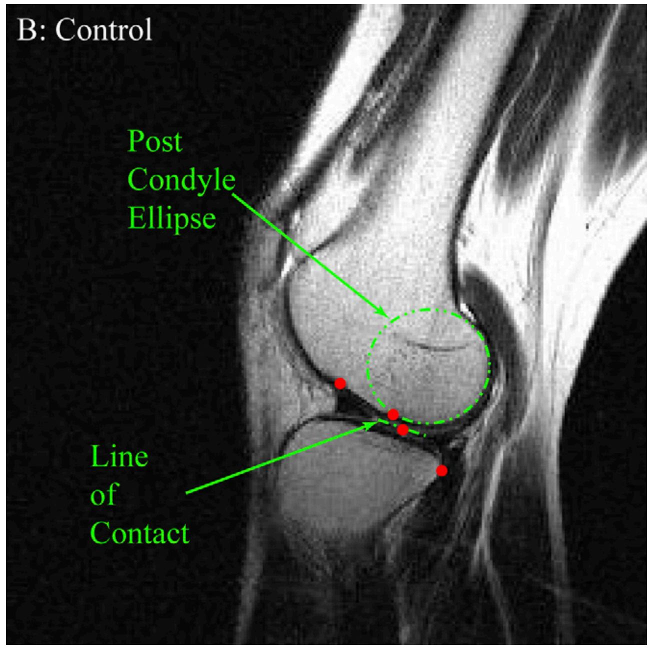

Fig. 3-B

Figs. 3-A through 3-D Magnetic resonance imaging measurements in the safe (Figs. 3-A and 3-B) and provocative (Figs. 3-C and 3-D) positions. Fem = femoral, and Tib = tibial. **Fig. 3-A** The control (safe) position. The femoral shaft line was the line that bisected the angle created by two lines (dashed) that defined the anterior (Fa) and posterior (Fp) femoral shaft just proximal to the sulcus groove. The tibial plateau line paralleled the tibial plateau. **Fig. 3-B** The control (safe) position, shown with use of the same base figure as Figure 3-A, but with different markers. The lateral posterior femoral condyle was visually fit with an ellipse (Post Condyle Ellipse). The line of contact (dashed straight line) was visually defined. Post = posterior. The red dots match those shown in Figure 3-D to demonstrate how the points move between the control and the provocative position.

board. In total, nine magnetic resonance imaging scans (three in each position, with multiple images per each scan) were acquired in an open 0.6-T standing magnetic resonance imaging scanner (Fonar, Melville, New York). The first scan was a low-resolution scout image. The second was a two-dimensional gradient-echo axial scan (with a resolution of 0.67 mm by 0.67 mm by 5.0 mm) that assessed the area from the beginning of the femoral condyles to the tibial tuberosity. The image at the superior aspect of the femoral epicondyles was used to define the location and orientation of the final two-dimensional sagittal-oblique gradient-echo recall scan (with a resolution of 0.75 mm by 0.75 mm by 4.5 mm). In this third scan, the scan plane was perpendicular to the line connecting the posterior aspect of the condyles, and the number of images was sufficient to capture the full width of the femur from medial to lateral. All patient and position identifiers were removed from the data so that one author (F.T.S.) was blinded to the subject, the limb position, and the order of limb position sequences. The subject order and the order of limb position sequences were randomized before analysis. This author quantified all measures on the magnetic resonance images. This same author repeated all measures five months after the initial measurements were made. The images were reordered by an outside investigator so that the author was blinded to the subject, limb position, the order of the limb position, and the original measurements. One subject moved during the image acquisition, causing image blurring. Because of this blurring, the identification of anatomical landmarks was imprecise. Thus, this one dataset was eliminated.

One angular and three distance measurements were made from the reference slice, defined as the first sagittal-oblique slice containing the medial edge of the fibular head[18]. All measurements were quantified with use of ImageJ (National Institutes of Health, Bethesda, Maryland)[19,20]. To acquire these measures, two lines and four points were identified (Figs. 3-A through 3-D): the femoral shaft line, the tibial plateau line, the point of contact, the femoral sulcus point, the most anterior point on the circular posterior portion of the condyle, and the posterior tibial point. The point of contact was determined by drawing a line (contact line) where the femur and tibia were in contact. The midpoint of this line was used as the point of contact. The most anterior point on the circular posterior portion of the condyle was determined by first creating a circle to fit the circular posterior portion of the lateral femoral condyle. The most anterior point on the circular posterior portion of the condyle was selected as the first point on the anterior aspect of the circle that was no longer contacting the joint surface. With use of these markers, the distances from the posterior tibial point to the point of contact, the point of contact to the femoral sulcus point, and the point of contact to the most anterior point on the circular posterior portion of the condyle were measured. The last measure, the point of contact to the most anterior point on the circular posterior portion of the condyle, was calculated between the

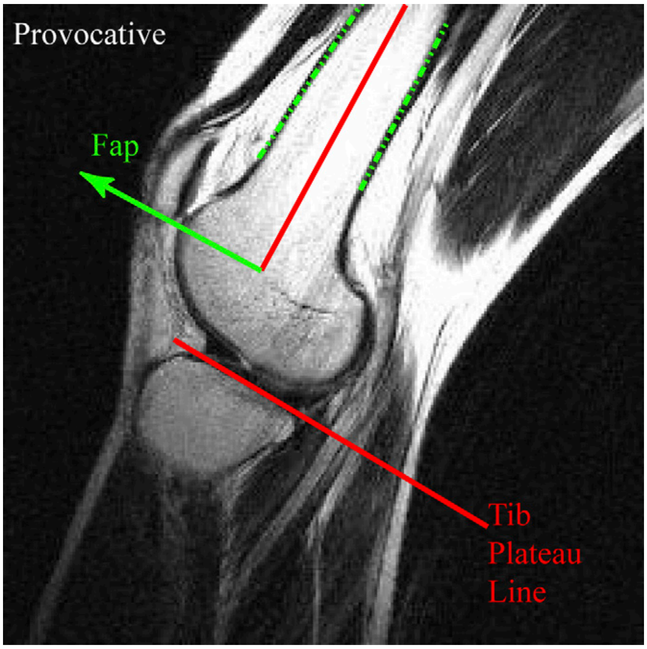

Fig. 3-C

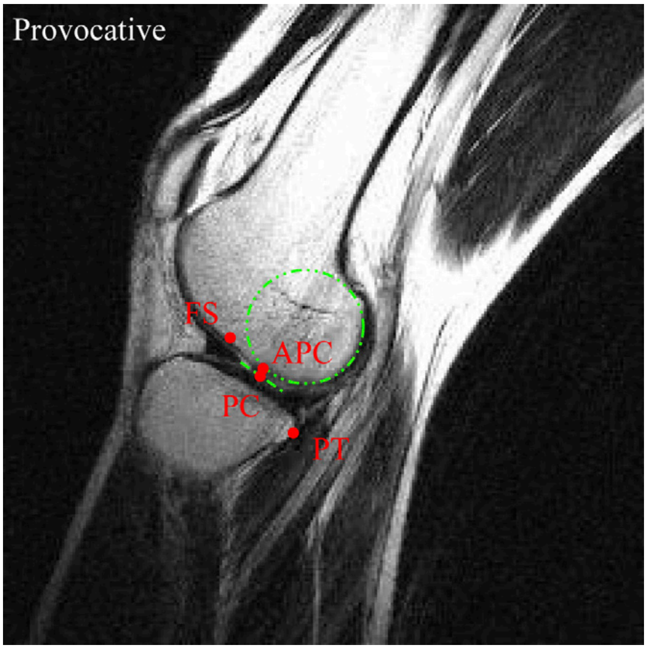

Fig. 3-D

Fig. 3-C The provocative position. Fap was defined as the line perpendicular to the femoral shaft line and defined the femoral anterior direction. **Fig. 3-D** The provocative position, shown with use of the same figure as Figure 3-C, but with different markers. The point of contact (PC) was defined as the midpoint of the line of contact (Fig. 3-B) between the tibia and femur. The femoral sulcus point (FS) was defined as the most indented point on the lateral femoral condyle sulcus of the center of the most convex surface. The most anterior point on the circular portion of the posterior aspect of the condyle (APC) was defined as the point at which the posterior condyle ellipse (Fig. 3-B) and femoral surface lost contact. The posterior tibial point (PT) was defined as the most posterior point on the tibia.

two points in the femoral anterior direction only, defined as the direction perpendicular to the femoral shaft line in the reference image. The tibial plateau angle was defined as the angle between the femoral shaft line and the tibial plateau line.

Statistical Analyses

An a priori power analysis showed that twenty subjects were required to detect a 1-mm difference in distance, assuming a two-sided Student t test, a power of 0.80, a significance level of 0.05, and a common variance that was twice the image resolution (1.5 mm). A two-way repeated-measures analysis of variance was used to assess main effects and interaction effects for two repeated-measurement trials (test one and test two) in each of three positions (safe, provocative, and exaggerated provocative). Thus, the two repeated factors were test and position. Three distances and one angle were measured twice

TABLE I Measurements of Tibiofemoral Alignment

Position*	Test†	Posterior Tibial Point to Point of Contact‡ *(mm)*	Point of Contact to Femoral Sulcus Point‡ *(mm)*	Point of Contact to APC‡ *(mm)*	Tibial Plateau Angle‡ *(deg)*
Safe	1	15.83 ± 2.33	12.74 ± 3.64	−3.62 ± 3.30	72.50 ± 8.31
	2	15.80 ± 1.80	12.17 ± 2.65	−3.11 ± 2.45	73.07 ± 8.56
Provocative	1	16.78 ± 2.28	10.54 ± 3.88	−0.27 ± 3.27	85.51 ± 10.97
	2	16.96 ± 2.76	10.74 ± 3.15	0.08 ± 3.29	85.75 ± 11.01
Exaggerated provocative	1	18.63 ± 3.33	7.78 ± 3.79	2.03 ± 4.77	94.51 ± 9.67
	2	18.70 ± 3.28	7.92 ± 3.50	2.83 ± 4.71	95.27 ± 8.96

*Position refers to the limb alignment. †Test refers to the first (1) or second (2) measurements. The two testing conditions were separated by five months. ‡The values are given as the mean and the standard deviation. APC = the most anterior point on the circular posterior portion of the condyle.

TABLE II Interclass Coefficients

	Interclass Coefficient†			
Position*	Posterior Tibial Point to Point of Contact	Point of Contact to Femoral Sulcus Point	Point of Contact to APC‡	Tibial Plateau Angle
Safe	0.876	0.840	0.793	0.980
Provocative	0.942	0.812	0.869	0.994
Exaggerated provocative	0.975	0.947	0.917	0.982

*Position refers to the limb alignment. †The coefficients are based on a single researcher acquiring all four measures on all twenty-four subjects in two different testing sessions (five months apart). All were significant at the $p < 0.001$ level. ‡APC = the most anterior point on the circular posterior portion of the condyle.

in each position such that four variables were assessed in separate two-way analyses of variance. Main and interaction effects were further examined with post hoc Tukey tests ($p < 0.05$). Intraclass correlation coefficients were used to examine intrarater reliability for each distance or angle measurement in each of the three positions.

Source of Funding
No external funding was received for the study.

Results

There were no significant differences in the measurements between the two testing trials (Table I). The interclass correlation coefficients were excellent, ranging from 0.793 to 0.994 (Table II). This showed that intrarater reliability did not influence the conclusions of this study.

The tibial slope relative to the femur was directed more inferior to superior in the provocative positions than in the safe position (Table I). As the limb alignment progressed from the safe to the exaggerated provocative position, the tibial plateau became more perpendicular to the femoral shaft (mean and standard deviation, 72.8° ± 8.4° for the safe position; 85.6° ± 10.9° for the provocative position; and 94.9° ± 9.2° for the exaggerated provocative position). The differences in all three positions were significant from each other (Table III).

The point of contact was closer to the sulcus on the lateral femoral condyle in the provocative positions than in the safe position (Table I, Fig. 4). Significant differences were found between all three positions (Table III).

As the limb changed position from safe to provocative to exaggerated provocative, the point of contact moved further anteriorly from the posterior tibial point (Table I, Fig. 4). Significant differences were found between all positions (Table III).

The lateral femoral condyle contacted the tibial plateau on its flatter anterior surface rather than the rounder posterior surface in the exaggerated provocative position (Table I, Fig. 4). In the safe position, the femur contacted the tibia on the more circular posterior portion of the condyle (indicated by the negative values for point of contact to the most anterior point on the circular posterior portion of the condyle). In the provocative position, contact occurred at the transition from the rounder posterior portion of the condyle to the flatter anterior portion of the condyle. These findings indicate that the point of contact moved from the rounder, posterior aspect of the lateral femoral condyle to the flatter, anterior aspect of the lateral femoral condyle as the limb transitioned from the safe to the provocative positions. Significant differences were found between all positions (Table III).

TABLE III Average Differences in Tibiofemoral Alignment Between Positions

	Average Differences*			
Parameter	Posterior Tibial Point to Point of Contact *(mm)*	Point of Contact to Femoral Sulcus Point *(mm)*	Point of Contact to APC† *(mm)*	Tibial Plateau Angle *(deg)*
Safe compared with provocative	−1.06	1.82	−3.27	−12.85
Provocative compared with exaggerated provocative	−1.79	2.78	−2.53	−9.26
Safe compared with exaggerated provocative	−2.85	4.60	−5.80	−22.11

*All values were significant, with a p value of <0.001 for all except for two values: −1.06 ($p < 0.05$) and 1.82 ($p < 0.01$). †APC = the most anterior point on the circular posterior portion of the condyle.

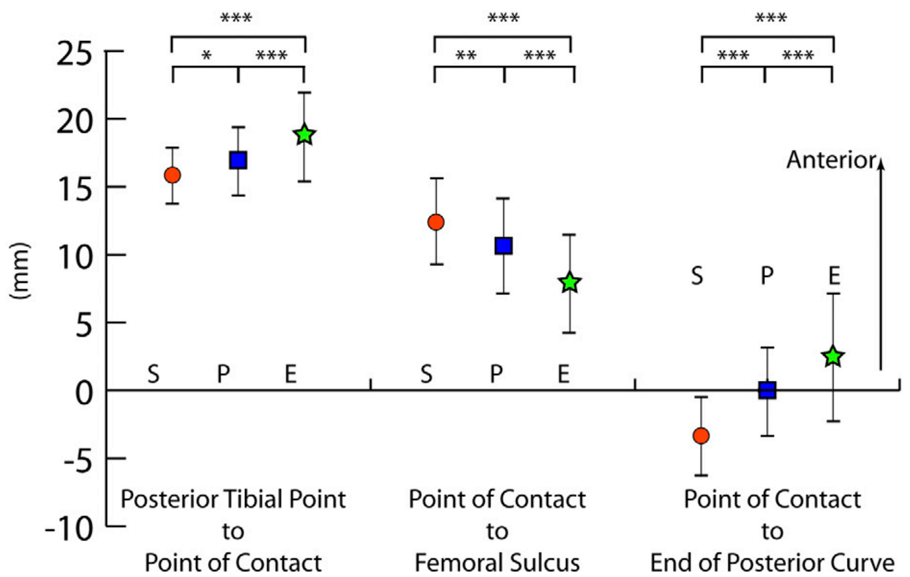

Fig. 4

Measures of tibiofemoral placement (mean and standard deviation). The circle, square, and star represent the safe (S), provocative (P), and exaggerated provocative (E) positions, respectively. A positive value indicates that the point of contact (PC) was anterior to the posterior tibial point, that the femoral sulcus (FS) was anterior to the PC, or that the most anterior point on the circular posterior portion of the condyle (APC) was anterior to the PC. A significant difference between two positions is indicated by a bar. *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$.

Discussion

To our knowledge, this study is the first to quantify an in vivo difference in tibiofemoral alignment during simulated landing positions. The altered tibiofemoral alignment in the provocative positions aligns the knee in a position closer to the subluxated position where bone bruises occur[14] with anterior cruciate ligament rupture, thereby potentially exposing the knee to an anterior cruciate ligament injury. Because of the risk of anterior cruciate ligament injury, impact forces were not applied to the knee in the study to confirm subluxation.

In the current study, a significant difference was found in the relationship of the femoral axis to the tibial plateau (an effective increase of the tibial slope) on the basis of the limb position. Geometrically, this finding is logical: as the knee becomes more extended in the provocative positions, the angle between the tibial plateau and the femoral shaft increases (Fig. 5). More importantly, with the increased hip flexion in the provocative positions, the angle of the tibial plateau relative to the gravity vector increases. This increased angle may increase the risk of the lateral femoral condyle sliding posteriorly down the tibial plateau (gravitational subluxation), which could strain or tear the anterior cruciate ligament with a compressive force. Previous studies[21,22] have shown conflicting results as to whether the posterior tibial slope (referenced off the tibia alone) is increased in subjects incurring noncontact anterior cruciate ligament injury compared with that of control subjects. Yet, it has been shown that during weight-bearing, anterior tibial translation increases as the tibial slope becomes greater. Dejour and Bonnin[23] found a 6-mm increase in anterior tibial translation with monopodal stance for every 10° increase in tibial slope.

The clinical effect of increasing the posterior tibial slope with a tibial osteotomy has been studied in canines with deficient anterior cruciate ligaments[24]. A combination of a weight-bearing axial compressive force and the increased posterior tibial slope was found to generate an anterior tibial thrust[24]. Therefore, a popular treatment for an anterior cruciate ligament deficient knee in canines is an osteotomy that decreases the posterior tibial slope[25,26]. This so-called tibial plateau-leveling osteotomy has been shown to convert an anterior tibial shift to a posterior tibial shift with an axial weight-bearing load[25]. The amount of anterior or posterior shift depends on the amount of axial force applied and the tibial slope[25]. In humans, it has also been shown that transition from non-weight-bearing to weight-bearing is associated with anterior translation of the tibia[27-30]. Several authors[23,24,31,32] have shown that combining an axial weight-bearing compressive force with increased tibial posterior slope causes an anterior tibial force in knees with either intact or deficient anterior cruciate ligaments. These results concur with the current findings that an effective increase in the slope of the posterior tibial plateau may promote an anterior tibial thrust, thereby predisposing the anterior cruciate ligament to injury.

The increased risk of anterior cruciate ligament injury with greater tibial slope is compounded by the impulse forces applied to the limb during a one-limb landing. The previous study on which this work is based showed that athletes who incur an anterior cruciate ligament tear land in a less plantar flexed ankle position and achieve a flat-footed position on the average 50% earlier than control athletes[11]. This implies that the calf muscles do not have sufficient time to absorb the ground reaction forces and the axial loads are transmitted to the knee, increasing the compressive or impulse force. Thus, the plantar flexed ankle in the safe position protects the anterior cruciate ligament through a reduction in the impact force resulting from an increase in the contact force dissipation time (impulse force is inversely proportional to the time the force is applied).

It is well known that most noncontact anterior cruciate ligament injuries (80%) are associated with bone bruises on the lateral side of the joint[14,15], indicating a lateral shift between the lateral femoral condyle and the lateral tibial plateau. There are several possible reasons why the pivot shift with anterior cruciate ligament rupture occurs on the lateral side of the joint rather than on the medial side. This study showed that the distance from the lateral compartment point of contact to the sulcus on the lateral femoral condyle is reduced in the provocative positions. Similarly, the point of contact moved anteriorly, relative to the posterior aspect of the tibia, as the limb transitioned from the safe to the provocative position. These findings indicate that the provocative positions place the knee in a vulnerable position, which is closer to the subluxated position where the bone bruises occur.

This study has also shown that as the limb moves toward the more provocative positions, the point of contact moves from the rounder posterior portion of the lateral femoral condyle to the flatter anterior portion of the lateral femoral condyle (greater radius of curvature). The area of contact between the articular surfaces on the medial side of the joint is greater than the area of contact on the lateral side of the joint[33]. In addition, the lateral tibial plateau is more convex than the concave medial tibial plateau. Therefore, when contact occurs between the flatter anterior portion of the lateral femoral condyle and the convex lateral tibial plateau (as is the case in the provocative positions), there is a greater probability of sliding (pivot shift) instead of rolling.

This study was limited in the finite number of limb positions examined. Although a range of limb positions may occur during noncontact anterior cruciate ligament injury, the average safe and at-risk limb positions were selected on the basis of a previous study[11]. In the current study, a third position, exaggerated provocative, was added for statistical robustness. In addition, there may have been flaws in the exact positioning of the lower extremity joints with a goniometer or in holding the limb position during scanning. However, the consistent trend between the three positions indicates that this variability was likely small. Because of time constraints of holding the limb in one position, coronal images to determine varus and valgus alignment of the knee were not acquired in this study. To understand the injury mechanics completely, frontal plane alignment and rotational forces need to be assessed in future studies.

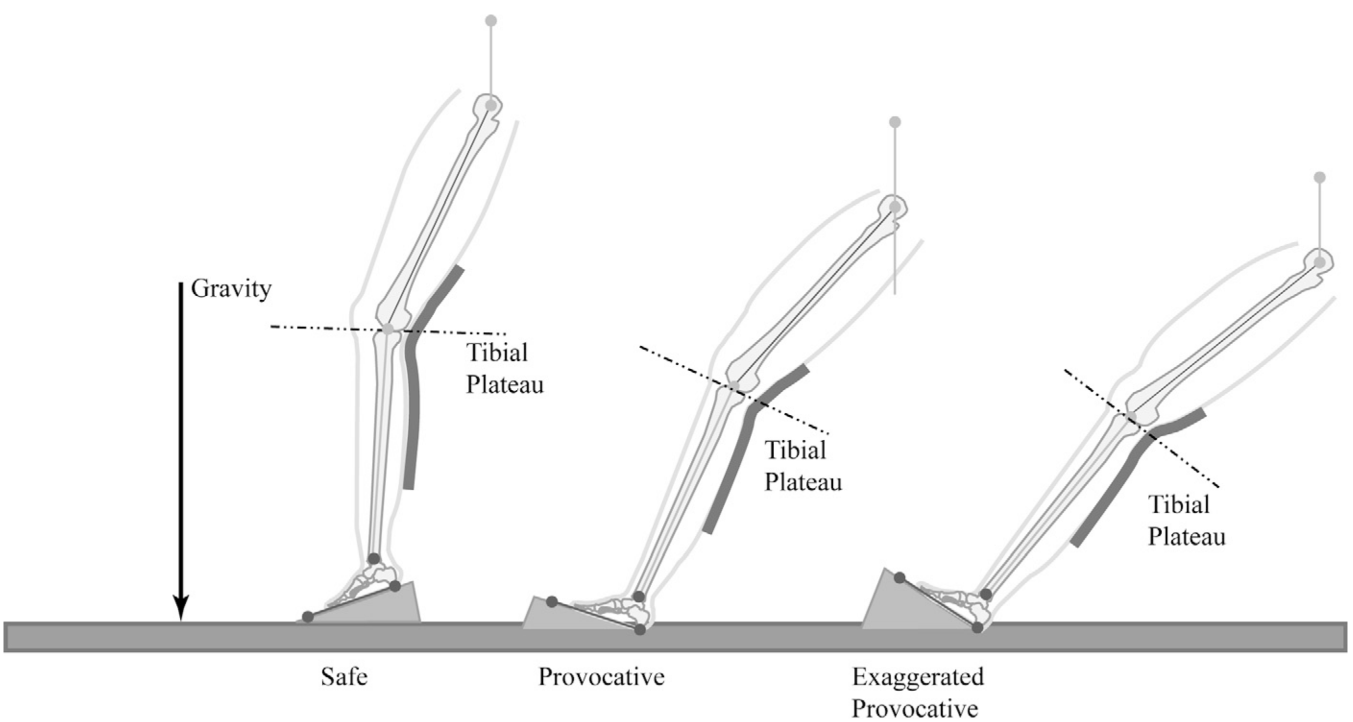

Fig. 5

Pictorial representation of the tibial plateau as the patient is transitioned from the safe to the provocative position and from the provocative to the exaggerated provocative position.

In summary, standing magnetic resonance images of safe and provocative landing positions have helped to elucidate numerous factors that may predispose an individual to a noncontact anterior cruciate ligament injury. The current study showed that, in the provocative positions, the tibial slope relative to the femur is directed more inferior to superior, the point of contact is closer to the sulcus on the lateral femoral condyle, and the lateral femoral condyle contacts the tibial plateau on its flatter anterior surface compared with its rounder posterior surface. These changes in the tibiofemoral alignment in the provocative positions may increase the risk of anterior cruciate ligament injury. ■

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