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Determination of the Position of the Knee at ACL rupture for Males versus Females by an Analysis of Bone Bruises

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Abstract

Background—The incidence of anterior cruciate ligament (ACL) rupture is 2-4 times higher in female athletes as compared to their male counterparts. As a result, a number of recent studies have addressed the hypothesis that females and males sustain ACL injuries via different mechanisms. The efficacy of prevention programs may be improved by better understanding whether there are differences in injury mechanism between sexes.

Hypothesis/Purpose—To compare knee positions at the time of non-contact ACL injury between sexes. We hypothesized that there would be no differences in the position of injury.

Study Design—Descriptive laboratory study.

Methods—Clinical T2 weighted magnetic resonance (MR) images from thirty subjects (15 male and 15 female) with non-contact ACL rupture were reviewed retrospectively. MR images were obtained within 1 month of injury. Subjects had contusions associated with ACL injury on both the medial and lateral articular surfaces of the femur and tibia. Three dimensional models of the femur, tibia, and associated bone bruises were created via segmentation of MR images. The femur was positioned relative to the tibia in order to maximize bone bruise overlap, thereby predicting the bone positions near the time of injury. Flexion, valgus, internal tibial rotation, and anterior tibial translation were measured in the predicted position of injury.

Results—No statistically significant differences between males and females were detected in the position of injury with regard to knee flexion ($p=0.66$), valgus ($p=0.87$), internal tibial rotation ($p=0.26$), or anterior tibial translation ($p=0.18$).

Conclusion—These findings suggest that a similar mechanism results in ACL rupture in both male and female athletes with this pattern of bone bruising.

Clinical Relevance—This study provides a novel comparison of male and female knee position at the time of ACL injury that may offer information to improve injury prevention strategies.

Keywords

kinematics; rupture; bone contusion; imaging; MRI; injury mechanism

INTRODUCTION

The incidence of ACL rupture in female athletes is estimated to be 2-4 times higher when compared to their male counterparts.^{5, 47} Several factors have been suggested to account for this difference, including differences in lower extremity morphology, hormonal levels, neuromuscular control, and biomechanics.^{11, 20, 25, 26, 28, 36, 37} Given the potential for severe short and long term consequences following ACL rupture, there is much interest in the prevention of these injuries.^{40, 42, 59} Attempts have been made to utilize differences in female kinematics in order to target injury prevention training protocols toward females.^{22, 24, 38, 46, 53} However, prevention programs have thus far yielded mixed results.^{50, 54} The efficacy of prevention programs could potentially be improved by data quantifying differences in injury mechanism between sexes, which are not well understood.

A biomechanical difference between males and females that is often cited in the literature is that females have higher valgus (knee abduction) angles and moments during athletic tasks than males.^{27, 31, 37} Furthermore, it has been suggested that females with higher valgus angles during landing are at greater risk for ACL injury.²⁶ To this point, a number of recent studies have addressed the hypothesis that females and males sustain ACL injuries via different mechanisms.^{21, 48, 60, 62} Analysis of injury videos has provided support for the idea that valgus collapse, which refers to medial buckling of the knee, is a crucial component of the non-contact ACL rupture mechanism, particularly in females.^{34, 44} However, while analysis of video is advantageous in that it allows for direct observation of the motions occurring at the time of injury, this methodology is potentially limited in that it is difficult to determine the point in time of ACL rupture, and three-dimensional joint kinematics are challenging to infer from a two-dimensional video.^{32-34, 44} Thus, studies using alternative methodologies to investigate the differences in kinematic mechanisms of ACL rupture between males and females are warranted.

An alternative method of studying the ACL injury mechanism utilizes the presence of bone bruises or contusions that are present on the femur and tibia in the majority of ACL rupture patients.^{29, 49, 52} These bruises manifest as increased signal intensity on T2 weighted magnetic resonance images (MRI)^{6, 45, 52, 58, 62} and are believed to result from trabecular damage due to impact between articular surfaces near the time of injury. As such, these bone bruises may offer valuable insight into the knee position at the time of ACL rupture,^{6, 30, 58} allowing for comparison of knee positions between sexes.⁶² Although a previous comparison of male and female bone bruising found no differences in the location or severity of bone contusions accompanying ACL injury,⁶² there is currently minimal data that utilizes bone bruises to compare the knee position of males and females who have sustained an ACL rupture.

A recent study from our laboratory used a combination of MRI, 3D modeling techniques, and numerical optimization to predict the position of the knee at the time of ACL injury.³⁰ Specifically, 3D models of the knee joint were positioned to maximize the overlap of the femoral and tibial contusions using numerical optimization. Given the assumption that these contusions are the result of tibiofemoral impact at the time of injury, this method may provide a unique perspective into the position of the knee at the time of ACL injury.

Building on these principles, the aim of the present study was to use this methodology to compare knee positions between males and females at the time of non-contact ACL rupture, specifically to test if knee kinematic differences exist between females and males at the time of injury. Considering previous data suggesting similar patterns in the frequency of bone contusions between sexes,⁶² we hypothesized that there would be no significant differences in knee position at the time of injury between male and female subjects.

METHODS

Selection Criteria and MR Imaging

Institutional review board approval was obtained for this retrospective study. A total of 30 subjects (males: n=15, mean age: 22 years, range: 16-35 years; females: n=15, mean age: 21 years, range: 15-34 years) who had sustained non-contact ACL rupture were included. MR images were obtained at a single institution, and reviewed by a board certified musculoskeletal radiologist with more than 30 years of experience to confirm the presence of ACL rupture and associated bone contusions. Based on the results of Kim et al³⁰, this study was designed to detect a difference of 3° in valgus with 80% power for groups comprised of 15 subjects.

An inclusion criterion was that images for each subject demonstrate bone bruising on the tibial plateaus and femoral condyles in both the medial and lateral compartments. This criterion allowed for a unique solution to the numerical optimization for determining the knee position.³⁰ A recent analysis of bone contusion patterns demonstrated the presence of contusions in both compartments in the majority of male (89%) and female (84%) subjects with non-contact ACL injuries.⁶² MR images were obtained within one month of injury (male mean: 10 days, range: 0-24 days; female mean: 10 days, range: 3-27 days). The reviewed images were clinical, sagittal FSE (Fast Spin Echo) T2-weighted images with slice thicknesses of 3-4 mm; gap of 0.3-0.4 mm; field-of-view of 16 cm; matrix of 256×256 interpolated to 512×512 pixels; repetition time of 2850-4983.3 ms; and echo time of 57.5-75.4 ms. 17 subjects also demonstrated MR evidence of medial collateral ligament (MCL) grade 1 sprain (9 males and 8 females).

Model Creation and Analysis

Sagittal MR images were utilized to create three-dimensional (3D) models of the knee.^{1, 12, 13, 43, 61} The bony and articular surfaces of the femur and tibia were outlined on all MR images for each subject. The bone contusions were then outlined along the outer surfaces of the femur and the tibia. All segmentation was performed by a single investigator and reviewed by the same board-certified musculoskeletal radiologist. The segmented images

were then stacked and combined to create 3D models of each subjects' knee and bone bruises via 3D modeling software (Figure 1) (Rhinoceros 4.0; Robert McNeel and Associates).

Numerical optimization was used to position the femur and tibia so as to maximize the overlap of the bone contusion surfaces (Figure 2).

The femur was translated and rotated in 3D space relative to the tibia, which remained in a fixed position, to minimize the distance between evenly spaced points on the femoral and tibial bone contusions. Optimization was further constrained to minimize penetration of bony surfaces. This analysis was performed under the assumption that the contusions resulted from impact between the articular surfaces near the time of ACL injury.

After optimization, the position of the tibia relative to the femur was measured. Flexion, valgus, internal tibial rotation, and anterior tibial translation were measured using a previously described anatomic coordinate system based on the position and orientation of the long axis of the tibia relative to the transepicondylar axis of the femur.^{30, 57} Specifically, the long axis of the tibia was defined by a cylinder fit to the tibial shaft. A mediolateral axis was set perpendicular to the long axis of the tibia and tangent to the posterior aspects of the tibial plateaus. An anteroposterior axis was created orthogonal to the long and mediolateral axes of the tibia. Likewise, the long axis of the femur was defined by a cylinder fit to the femoral shaft.

Flexion angle was determined in the sagittal plane using the transepicondylar line as the axis of rotation. Valgus was measured as the angle between the long axis of the tibia and the transepicondylar line of the femur. Internal tibial rotation was measured in the axial plane as the angle between the mediolateral axis of the tibia and the transepicondylar line of the femur projected onto the tibial plateau. Anterior tibial translation was measured in the sagittal plane as the distance between the transepicondylar line of the femur and the origin of the tibial coordinate system. The position of the knee in the MR scanner served as the pre-optimization reference position while the optimized position was the predicted injury position (Figure 2). Differences between the MRI position and predicted injury position were reported, similar to gait analysis studies which use a quiet stance as a reference position.^{15, 55} A previous evaluation of the repeatability of this method demonstrated standard deviations of the femoral and tibial bone bruise surfaces within 1% of the total bone bruise surface area, and standard deviations of 0.9° of flexion, 0.8° of valgus, 0.1° of internal tibial rotation, and 0.1 mm of anterior tibial translation.³⁰

The data were summarized using routine descriptive statistics. Differences by sex in the kinematic measures were compared using independent t-tests. Fisher's exact test was used to test for sex differences in categorical variables (i.e. presence of MCL injury). Statistical significance was determined where $p < 0.05$.

RESULTS

With regard to patient characteristics, no statistically significant differences between the male and female cohorts were detected in mean age ($p = 0.52$), days from injury to MRI

scan ($p = 0.99$), or frequency of MCL sprain between males and females ($p = 1.00$). In terms of differences in position, no significant differences between the males and females were detected for flexion ($p = 0.66$), valgus ($p = 0.87$), internal tibial rotation ($p = 0.26$), or anterior tibial translation ($p = 0.18$) (Figure 3).

In the position of injury relative to the reference (MRI) position, females showed a mean of 24.6 mm of anterior tibial translation, 5.3° of internal rotation, 8.0° of valgus, and 20.2° of flexion. These values were similar to the mean of 26.9 mm of anterior tibial translation, 8.6° of internal rotation, 8.3° of valgus, and 18.4° of knee flexion that were measured in males.

DISCUSSION

The purpose of this study was to compare male and female knee positions near the time of ACL rupture. Numerical optimization was used to position 3D models of the femur and tibia such that the overlap of femoral and tibial bone contusions was maximized, thereby predicting the relative positions of the bones at the time of injury.³⁰ Our results show no statistically significant differences in the predicted position of injury between males and females. Therefore, in subjects with bone bruises on both the medial and lateral surfaces of the femur and tibia, these data suggest a similar mechanism of non-contact ACL injury for male and female athletes. Specifically, the results presented here suggest that landing on an extended knee is high risk for ACL injury in both males and females. Extension was accompanied by increased anterior tibial translation, internal tibial rotation, and valgus rotation in the predicted position of injury relative to the MRI position.

Previous data have indicated that a key function of the ACL is to resist anterior tibial shear forces that result in anterior translation of the tibia relative to the femur.⁸ Studies in cadavers have shown that simulated quadriceps loading results in ACL strain when the knee is positioned closer to extension.^{2, 16–18} *In vivo* studies have further clarified this mechanism by suggesting that quadriceps loading creates an anterior shear force on the tibia via the patellar tendon, which is oriented to pull more anteriorly on the tibia with decreasing flexion angles.^{14, 41} Thus, motions that result in quadriceps activation with the knee extended, such as landing with only slight knee flexion, may result in substantial anterior tibial shear forces. As the ACL is positioned to resist anterior tibial translation, these motions may strain the ACL and potentially increase propensity for injury. To this point, Fleming et al¹⁹ demonstrated increased ACL strain with increased anterior tibial shear force, particularly while bearing weight. DeMorat et al¹⁶ also investigated this mechanism utilizing 13 cadaveric knees fixed at 20° of flexion. With application of a simulated quadriceps force in this position, the knees demonstrated an average of 19.5 mm of anterior tibial translation, 2.3° of valgus, and 5.5° of internal tibial rotation in the injury position.

Furthermore, several *in vivo* studies have used imaging techniques to measure strain on the ACL.^{55–57} Such data may help to identify knee positions that have the potential to increase the risk of ACL rupture. These studies have consistently supported the hypothesis that ACL strain is maximized when the knee is close to full extension. Specifically, maximum ACL strains were observed when the knee was maximally extended during the mid-stance phase and just prior to heel strike during gait.⁵⁵ Similarly, when patients were asked to perform a

jump landing activity, they demonstrated peak ACL strain just prior to landing when knee flexion was minimal.⁵⁶ In another *in vivo* study, Utturkar et al⁵⁷ found that the maximum ACL length occurred when the knee was fully extended. ACL length decreased when the knee was positioned in 30° of flexion and further decreased when the knee was positioned to mimic valgus collapse. These findings are in agreement with *in vivo* studies of ACL strain during movement using implanted strain transducers,^{3, 4, 9, 35} which show peak strains near the time of landing with the knee in extension.^{9, 35} Studies by Beynnon et al^{3, 4} similarly indicate that strain on the ACL is reduced with increasing flexion.

Thus, there is ample evidence to suggest that increased ACL strain occurs in response to anterior tibial shear force resulting in anterior tibial translation. This may occur during quadriceps contraction prior to or following landing when the knee is extended. The data presented here similarly suggests that substantial anterior tibial translation occurred at the time of injury with the knee positioned close to extension. These findings are congruent with the results of Kim et al³⁰, which used the same technique as the present study. These findings are also in agreement with *in vivo* studies using imaging⁵⁵⁻⁵⁷ and cadaveric studies^{2, 16-18} that provide evidence to support the idea that landing with an extended knee is a high risk position for non-contact ACL rupture.

In the present study, we did not detect statistically significant differences in valgus positioning of the knee between males and females with an average of 8.3° measured for males and 8.0° for females. This magnitude of valgus angle is similar to the 5.0° reported by Kim et al³⁰ as well as the data from a cadaveric study which demonstrated a valgus angle increase of 2.3° induced by quadriceps loading at the time of ACL rupture.¹⁶ Furthermore, the results from this study with regard to valgus angulation at the time of injury are comparable to valgus angles measured near the time of ground impact obtained via videographic analyses.^{7, 27} Despite differences in the coordinate systems from which valgus angulation was measured between videographic analyses and the present study,⁵⁷ similar magnitudes of knee abduction angle (5-10°) were measured within 50 ms following ground contact in both injured and uninjured athletes.^{7, 27} Also consistent with our study, no statistically significant differences in knee abduction were observed between males and females near the time of ground contact.²⁷ On the other hand, at later time points following initial ground contact, these videographic studies reported significant differences in knee abduction angle between injured and uninjured athletes⁷ as well as between female and male injured athletes.²⁷ Specifically, average knee abduction angles of 38° were reported in injured subjects several frames after ground contact.⁷ In another study, injured female athletes progressed into an average maximum knee abduction angle near 40° as compared to 20° in injured male athletes 250 ms after initial ground contact.²⁷ However, some previous investigators have suggested that ACL injury may occur closer to the time of ground contact, prior to collapse into flexion and valgus.^{39, 44}

Given the similarity in the injury position between males and females with bone bruises on all four knee compartments (medial and lateral femur and tibia), the increased rate of ACL rupture in females may be related to differences in neuromuscular control or muscle activity, which may predispose female athletes to landing in an at-risk position (knee near full extension) rather than differences in injury mechanism. In line with this hypothesis,

Chappell et al^{10, 11} compared knee kinematics of uninjured male and female athletes performing a stop-jump task. These studies suggested a significantly greater peak proximal tibial anterior shear force in the landing phase for female athletes compared to male athletes.¹¹ A subsequent study demonstrated that female subjects showed significantly lower knee flexion angle and increased quadriceps activation when preparing to land from a stop-jump relative to males.¹⁰ Sigward et al⁵¹ similarly found higher quadriceps activation in females relative to males during side-step cutting. Taken together with our findings, these data suggest that differences in motion patterns may predispose female athletes to assume at-risk knee positions, such as landing in extension, although the position of the knee at the time of rupture may be similar between males and females. Further work in understanding these predisposing factors would be beneficial for injury prevention.

The methodology of bone bruise optimization operates under the assumption that bone contusions occur at or near the time of ACL rupture. Previous reviews of MR images after ACL rupture have demonstrated that the majority of these contusions are resolved within 6 weeks of injury.²³ This suggests that these contusions are a transient phenomenon associated with the injury. For this study, only patients with MRI-verified evidence of contusion to the medial and lateral compartments of both the tibia and the femur were included for analysis. While it has been suggested that lateral compartment bone bruising is more common than medial compartment bone bruising, more recent analyses of bone bruise patterns demonstrated that bruising in both medial and lateral compartments of both bones is common.^{58, 62} As stated above, Wittstein et al⁶² found that 84% and 89% of females and males, respectively, with non-contact ACL injuries had bone bruises in both medial and lateral compartments. Similarly, Viskontas et al⁵⁸ also demonstrated significant medial compartment bruising in non-contact ACL ruptures, with > 60% of individuals showing bruising on the medial compartment of the tibia. Additionally, the high incidence of medial meniscus tear with ACL rupture suggests that the medial compartment may be frequently impacted during ACL injury^{58, 62}. Although the current analysis strategy is limited to those with bone bruises on the femur and tibia in both compartments, bone bruising in both compartments is common within six weeks of ACL injury^{58, 62}.

Our findings have important implications regarding the prevention of ACL rupture. Given the devastating short and long-term effects of ACL rupture and the high rates of injury, considerable effort has been dedicated to developing injury prevention programs.^{22, 24, 38, 46, 50, 53, 54} This study supports the assertion that training to land and pivot with the knee in a more flexed position may play a key role in preventing injury in both males and females. Moreover, the findings of this study indicate that a similar mechanism of injury occurs in both males and females. Thus, investigating predisposing factors, such as aforementioned differences in motion patterns, may help reduce ACL injuries in females, as they may increase propensity for females to land in high risk positions. In the future, these analytical techniques can be extended by coordinating *in vivo* strain measurements^{14, 55-57} with analyses of bone bruising patterns³⁰ to further elucidate at-risk knee positions.

In conclusion, optimization was used to maximize the overlap of tibial and femoral bone bruises seen on MR images in order to predict the knee position at the time of non-contact ACL injury and to compare gender differences in the mechanism of injury. No statistically

significant differences were detected between males and females in regards to knee flexion, valgus, internal tibial rotation or anterior tibial translation in the predicted position of injury. This kinematic similarity suggests that for the participants included in our study (individuals with bruises on both medial and lateral surfaces of the femur and tibia), males and females experienced similar mechanisms of injury. Furthermore, our data suggest that substantial anterior tibial translation occurred with the knee near full extension at the time of injury, potentially occurring as a result of quadriceps contraction.

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Figure 1.

Bone surfaces (orange) and bone contusions (green) were outlined on each MRI and compiled to create 3D models of each knee.

Figure 2. Sagittal view of the MRI (left) and the predicted (right) position of the knee at the time of injury with overlapping of the femoral condyle bruises (blue) and tibial plateau bruises (red).

Figure 3. Means and 95% confidence intervals of knee flexion ($p=0.66$), valgus ($p=0.87$), internal tibial rotation ($p=0.26$), and anterior tibial translation ($p=0.18$) by sex.