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Video Analysis of Anterior Cruciate Ligament Injury

Abnormalities in Hip and Ankle Kinematics

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Background: Most anterior cruciate ligament research is limited to variables at the knee joint and is performed in the laboratory setting, often with subjects postinjury. There is a paucity of information on the position of the hip and ankle during noncontact anterior cruciate ligament injury.

Hypothesis: When landing after maneuvers, athletes with anterior cruciate ligament injury (subjects) show a more flatfooted profile and more hip flexion than uninjured athletes (controls).

Study Design: Case control study; Level of evidence, 3.

Methods: Data from 29 videos of subjects were compared with data from 27 videos of controls performing similar maneuvers. Joint angles were analyzed in 5 sequential frames in sagittal or coronal planes, starting with initial ground-foot contact. Hip, knee, and ankle joint angles were measured in each sequence in the sagittal plane and hip and knee angles in the coronal plane with computer software. The portion of the foot first touching the ground and the number of sequences required for complete foot-ground contact were assessed. Significance was set at $P < .05$.

Results: In sagittal views, controls first contacted the ground with the forefoot; subjects had first ground contact with the hindfoot or entirely flatfooted, attained the flatfoot position significantly sooner, had significantly less plantar-flexed ankle angles at initial contact, and had a significantly larger mean hip flexion angle at the first 3 frames. In coronal views, no significant differences in knee abduction (initial contact) or hip abduction angle were found between groups; knee abduction was relatively unchanged in controls but progressed in subjects.

Conclusion: Initial ground contact flatfooted or with the hindfoot, knee abduction and increased hip flexion may be risk factors for anterior cruciate ligament injury.

Keywords: anterior cruciate ligament; ground-reaction forces; injury prevention

The mechanisms of noncontact anterior cruciate ligament (ACL) injury have not been clearly defined. These theories may be divided into extrinsic (perturbations, shoe-surface interface interaction, and bracing) and intrinsic (anatomical, hormonal, and neuromuscular) variables.[13] Anatomical differences have focused on a decreased notch width, which was initially thought to cause impingement of the ACL.[30] More recent literature has implied that a smaller notch

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correlates with a smaller, weaker ACL.[26] Hormonal theories have proposed that estrogen causes ligamentous laxity of the ACL, predisposing to injury.[32,35] Another popular theory that has received significant attention in the literature is the antagonist-agonist relationships.[5,33] The quadriceps has been hypothesized to contract at the point of impact leading to an anterior vector on the proximal tibia that may lead to rupture of the ACL.[13]

Despite intense study of ACL injury during the past 3 decades, the exact mechanisms of this injury are unknown. Previous reports on actual ACL injuries were based on interviews with the athletes or descriptive analyses of videotape footage.[5,18,22] These sources are not ideal for analysis because athlete interviews are subjective and prone to inaccuracies secondary to trying to recall the details of the abrupt event[5,25] that may have occurred a substantial amount of time previously. Simple visual inspection techniques also have poor accuracy and precision, even after the examiners have undergone an analysis training program.[17] In addition, to our knowledge, no previous study has used videos of uninjured athletes for comparison.

The purposes of our study were to determine the foot position and lower extremity joint angles of athletes at the time of ACL injury, to compare these results with those of uninjured athletes, and to propose an axial force theory to explain a major component of ACL injury. The authors hypothesized that, compared with uninjured athletes performing comparable athletic maneuvers (controls), athletes with ACL injury (subjects) would show a more flatfooted profile and a more flexed hip at landing after a jump or after a sharp deceleration maneuver.

MATERIALS AND METHODS

Data Collection

During a 12-year period (1995-2007), the authors requested from physicians, athletic trainers, patients, and the National Basketball Association (NBA Entertainment Inc [NBA and WNBA games]) videotapes of athletes captured during incidences of ACL injury that resulted in ACL reconstruction. Seventy such videotapes were collected. Our study was exempt from institutional review board approval. Criteria for inclusion of a video in our study were as follows: (1) good quality, with the camera angle approximating a sagittal (lateral) or coronal (anterior or posterior) view of the athlete; (2) visualization of the foot contacting the ground; (3) unobscured view of the athlete; and (4) no or minimal contact during the athletic maneuver. Minimal contact included being touched by an opponent, such as shoulder to shoulder contact during a rebound. Videotapes were excluded if the athlete was being tackled or pushed by an opponent or if there was any direct contact to the knee.

Twenty-nine injury videos met the criteria (as assessed by 1 author, B. P. B.): 12 from a sagittal view (8 women, 4 men), 6 from a coronal-anterior view (3 women, 3 men), and 11 from a coronal-posterior view (7 women, 4 men). Injury conditions, eg, type of sport, level of play, game or high-intensity practice situation, level of contact (none or minimal), activity being performed (vertical jump, broad jump, or deceleration), whether the player was on offense or defense, whether the subject was holding a ball, and whether another player was in close proximity (being guarded or guarding another athlete) were tabulated.

The subjects had been participating in the following sports activities: basketball, 14 (5 professional, 6 college, 3 high school); professional handball, 7; soccer, 3 (2 professional, 1 college); football, 3 (1 professional, 2 college); competitive cheerleading, 1 (college); and gymnastics, 1 (college). Most injuries occurred during game situations (25 of 29, 86.2%); the remainder occurred in practice drills (2, 6.9%) or competition (2, 6.9%; 1 cheerleader and 1 gymnast). The same author classified the injuries by degree of participant contact (minor contact or a perturbation, 8, 27.6%; no contact, 21, 72.4%) and by activity at the time of injury (deceleration, 18, 62.1%; landing from a broad-jump maneuver; 5, 17.2%; and landing from a vertical jump, 6, 20.7%). More women than men (14, 77.8% and 4, 22.2%, respectively) had been performing a decelerating maneuver; a landing activity was associated with injury more often in men than in women (7, 63.6% and 4, 36.4%, respectively). Most subjects were on offense (23, 85.2%) rather than defense (4, 14.8%); 2 subjects were participating in a competition rather than team sports (1 cheerleader, 1 gymnast). All subjects on offense were holding a ball, had a soccer ball at their feet, or had just released a ball before the foot contacted the ground; all defensive players were guarding the player with the ball. Twenty-six (96.3%) of the 27 subjects who were playing team sports had an opposing player in close proximity (within 3 feet). At the first sequence of initial foot contact with the ground, 21 subjects (72.4%) had weightbearing on only 1 leg; 8 (27.6%) had bilateral foot contact with the ground.

The same author (B. P. B.) selected and assessed 27 videotapes of professional (25) and collegiate (2) basketball players (controls) performing similar decelerating or landing maneuvers during game situations: 12 from a sagittal view (8 women, 4 men), 8 from a coronal-anterior view (4 women, 4 men), and 7 from a coronal-posterior view (3 women, 4 men). Basketball was the sport of choice for the controls because of the availability of high-quality videos from professional and collegiate matches and because of the close proximity of the camera to the athletes. Of the 27 controls, 12 (44.4%) sustained minor contact or a perturbation, and 15 had no contact (55.6%). At the time of the recorded maneuver, the activity at ground contact was landing from a vertical jump (16, 59.3%), landing from a broad jump (5, 18.5%), and deceleration (6, 22.2%); the game position was offense for 18 (66.7%) and defense for 9 (33.3%). Twenty-six (96.3%) of the controls were estimated to have had an opposing player in close proximity (within 3 feet) at the time of the recorded impact with the ground. At initial contact, 24 (88.9%) of the controls had weightbearing on only 1 leg; 3 (11.1%) had bilateral contact with the ground.

Video Editing and Analysis

The video recordings were edited using Adobe Premiere Pro (version 2.0, Adobe Systems Inc, San Jose, California) and deinterlaced to achieve a 30-Hz (frames per second) effective frame rate via Adobe Photoshop (version CS2, Adobe Systems Inc). Each video was converted to 5 consecutive still frames, starting with the sequence in which the foot initially contacted the ground (initial contact), which were stored as TIFF files. Image J was used to measure joint angles after drawing lines based on the landmarks described below.[1,24] All measurements were performed by the same author (B. P. B.) for consistency.

For the sagittal view analysis, the camera was on the same side as the affected leg in subjects and controls. The angles measured included ankle dorsiflexion/plantar flexion, knee flexion, and hip flexion. The ankle joint was measured as the angle between the axis of the lower leg and the plantar surface of the shoe.[10] The knee angle was measured between a line connecting the superior tip of the greater trochanter to the midpoint of the lateral knee at the joint line, and a line connecting the midpoint of the lateral knee at the joint line to the distal and anterior point of the distal tip of the fibula. The hip angle was measured by connecting a line from the superior tip of the acromioclavicular joint on the affected side to the superior tip of the greater trochanter and a line from the superior tip of the greater trochanter to the midpoint of the lateral knee at the joint line.

The portion of the foot (hindfoot, midfoot, forefoot, or combination) touching the ground was also calculated for each frame by drawing a line on the plantar portion of the shoe touching the ground and dividing by a line drawn along the entire plantar portion of the shoe. The joint angles were assessed at the first point where the entire foot was flat on the ground, and the number of frames until the foot was 100% flat on the ground was calculated.

The anterior and posterior views were analyzed together to assess the coronal position. For the anterior view analysis, the knee abduction angle and the hip abduction/adduction angle were measured. The knee abduction angle was measured using the anatomic axis of the leg: a line was drawn from the anatomic axis of the femur to the center of the knee joint at the joint line and a line from the same point on the knee to the center of the tibia at the ankle joint.[28] The hip abduction or adduction angle was measured by connecting a line from the anterior superior iliac spine and the axis of the femur with a line drawn from the anterior superior iliac spine to the ground and perpendicular to the pelvis (line drawn from anterior superior iliac spine on the right and left; the waistband of the athlete's shorts was used for guidance).[11]

For the posterior view analysis, the knee abduction angle and the hip abduction/adduction angle were measured. The knee abduction angle was calculated as the angle between a line drawn from the anatomic axis of the femur to the center of the knee at the joint line and a line from the same point at the knee to the center of the distal tibia at the ankle joint. The hip abduction/adduction angle was calculated by drawing a line from the posterior superior iliac spine along the axis of the femur to the midpoint of the knee at the level of the joint line and a line from the posterior superior iliac spine to the ground perpendicular to the pelvis (line drawn from the right to left posterior superior iliac spine; the waistband of the athlete's shorts was used for guidance).

Statistical Analysis

All angle measurements were imported into SAS 8.02 (SAS Institute Inc, Cary, North Carolina) for statistical analysis. Two-sided t tests were performed to assess if there were statistically significant differences between subjects and controls, male and female subjects, female subjects and female controls, male subjects and male controls, or male and female controls. Gender comparisons were performed to assess if there were differences in the leg position at the time of injury for men compared to women. Two-sided t tests were also performed for the angles on the first sagittal view when the foot was 100% flat on the ground. Significance was set at $P < .05$. Intraclass coefficients (ICC) were calculated to assess the reproducibility of the angle measurements at each video frame sequence at 3 different times. The single rater (B. P. B.) repeated the measured videotape frames of 4 angles in a total of 10 subjects (2 angles/6 subjects; 2 angles/4 subjects). The estimated ICCs ranged from 0.32 to 0.99, with 18 of the 20 coefficients greater than 0.95.

RESULTS

Sagittal Views

Foot Position. The initial ground contact for all subjects was the hindfoot (Figure 1A) or the entire foot flat; that for controls, was the forefoot or a combination of the forefoot and the midfoot (Figure 1B). The subjects reached a flat-footed position significantly sooner (mean video frame, 1.5 ± 0.5 sequences) than did the controls (mean video frame, 3.08 ± 0.9 sequences; $P < .0001$).

Ankle Angle. At initial contact, the ankle angle was significantly less plantar-flexed in subjects (mean, 10.7° ± 9.6°) than in controls (mean, 22.9° ± 10.1°) (Figure 2). After initial contact, the ankle angle remained relatively unchanged in the subjects (range, 15.0° ± 10.2° to 6.6° ± 15.3°), but it steadily progressed from a plantar-flexed (mean, 22.9° ± 10.1°) to a dorsiflexed (mean, –20.9° ± 9.4° at frame 5) position in the controls, a mean difference of 43.8° ± 7.2° from initial contact (frame 1) to frame 5. Except for the second sequence, all ankle angles were significantly different between subjects and controls (Figure 2). After the second sequence, the ankle angles in the subjects remained in a slightly plantar-flexed position, whereas those for the controls were significantly more dorsiflexed. No significant difference between the male and female subjects was found. There was a significant difference in ankle position between female subjects and female controls as well as male and female controls for all frames except frame 2. There was also more ankle plantar-flexion (difference, 10.09° ± 10.87°) at frame 1 and more ankle dorsiflexion at frames 3 through 5 in male controls compared with male subjects, but the difference was not statistically significant.

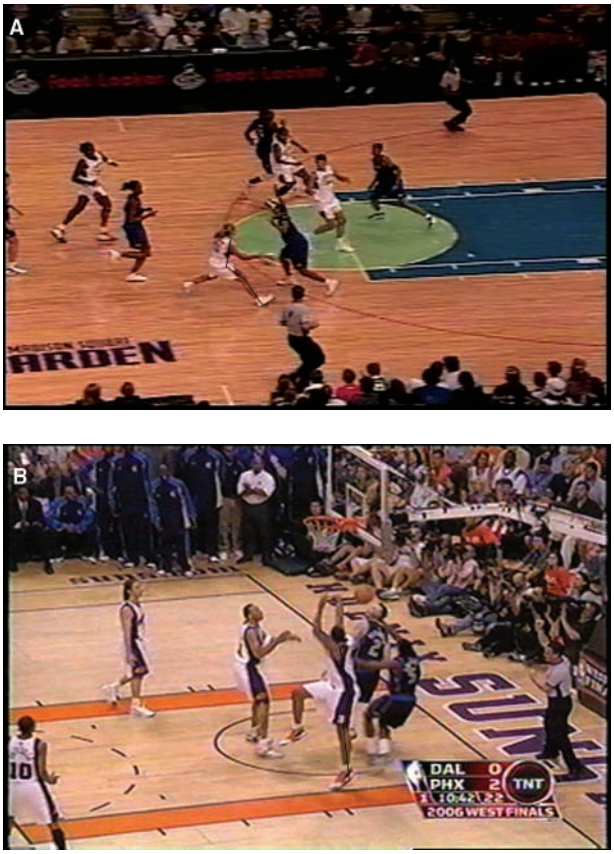

Figure 1. Frame 1 (initial foot contact with ground) of a subject (A) showing initial contact with the hindfoot and of a control (B) showing initial contact with the forefoot.

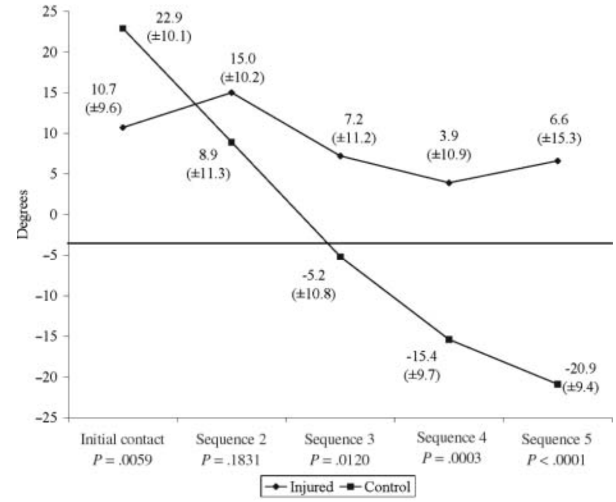

Figure 2. Sagittal ankle angles (mean ± SD) in subjects (injured) and controls for the 5 frames.

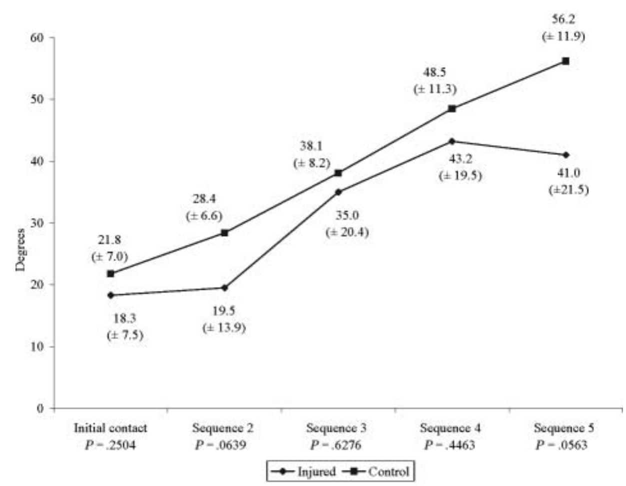

Figure 3. Sagittal knee angles (mean ± SD) in subjects (injured) and controls for the 5 frames.

Knee Angle. No significant difference in knee flexion angle between subjects and controls for the 5 frames was found (Figure 3). There was a trend toward less knee flexion in subjects, especially for frames 2 (P = .06) and 5 (P = .06), but it was not statistically significant. There were no significant differences in knee flexion between male and female subjects, female subjects and female controls, male and female controls, or male and female controls.

Hip Angle. For the first 3 frames, the hip was significantly more flexed in subjects than in controls (Figure 4). The mean hip angle for all 5 frames was 19.6° ± 15.1° more flexed for the subjects (52.4.6° ± 17.4°) than for the controls (33.4° ± 12.7°). No significant difference in hip flexion for the 5 frames between male subjects and controls or between male and female controls were found. For all 5 frames, there was significantly more hip flexion in the female subjects than in female controls: 58.9° ± 9.9° and 37.6° ± 11.2°, respectively (mean difference, 21.3° ± 10.6°). Female subjects had greater hip flexion than male subjects in the first 3 frames, but the difference was not statistically significant; the differences were significant for frames 4 and 5.

100% of Foot Contacting Ground. In addition to comparing joint angles at frames 1 through 5, the joint angles were also assessed at the first frame in which the foot was 100% in contact with the ground (Figure 5). In this frame, the differences in all measured angles between the subjects and controls were significant; subjects had significantly less knee flexion and ankle plantar flexion and significantly more hip flexion.

Coronal Views

Knee Angle. No significant differences in mean knee abduction angles at initial contact between the subject and control groups or between any of the subgroups were found. The mean knee abduction moment at the point of impact was 5.5° ± 6.0° and 5.6° ± 6.7° in subjects and controls, respectively. After initial contact, the knee abduction moment remained relatively unchanged in the controls,

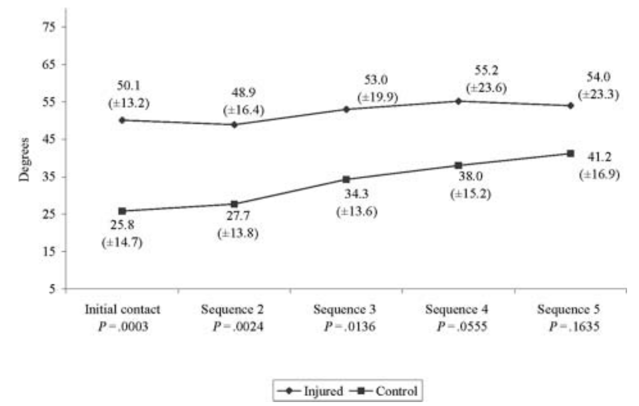

Figure 4. Sagittal hip angles (mean ± SD) in subjects (injured) and controls for the 5 frames.

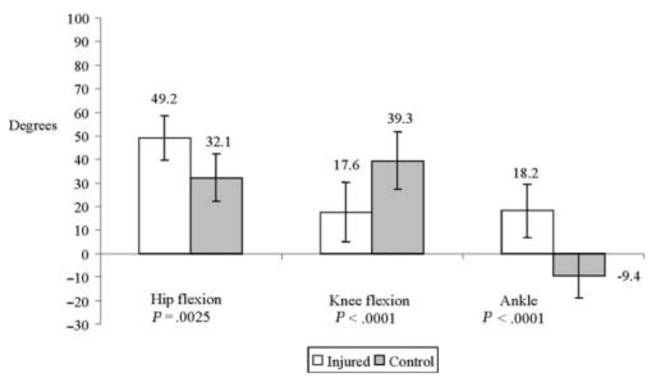

Figure 5. Sagittal joint angles (mean ± SD) in subjects (injured) and controls in the first frame of the sequence, in which the foot was completely flat on the ground.

but the subjects showed progressively more knee abduction with each sequence (Figure 6); the mean differences between subjects and controls for the third through fifth frames were significant. By the fifth frame, the mean knee abduction was 37.7° ± 21.0° and 9.0° ± 17.1° for subjects and controls, respectively (mean difference, 28.7° ± 19.5°). Male and female subjects had increased knee abduction during the 5 sequences, but female subjects had significantly more knee abduction than male subjects by the fifth frame. Although the knee abduction angle tended to be higher in female than in male controls, the only significant difference was at frame 2: in female controls, the knee abduction angle increased from a mean of 9.0° ± 8.4° at initial contact to a mean of 17.2° ± 23.1° in frame 5; there was little difference in the 5 sequences of the male controls. The overall mean for the 5 frames in female and male controls was 14.7° ± 11.5° and 4.3° ± 4.9°, respectively (mean difference, 9.8° ± 8.9°).

Hip Angle. No significant differences in hip abduction angle between the subjects and controls were found in any of the 5 frames (Figure 7), although the former showed a slight trend toward more hip abduction (overall mean difference, 3.7° ± 11.7°). For the 5 frames, the hip abduction

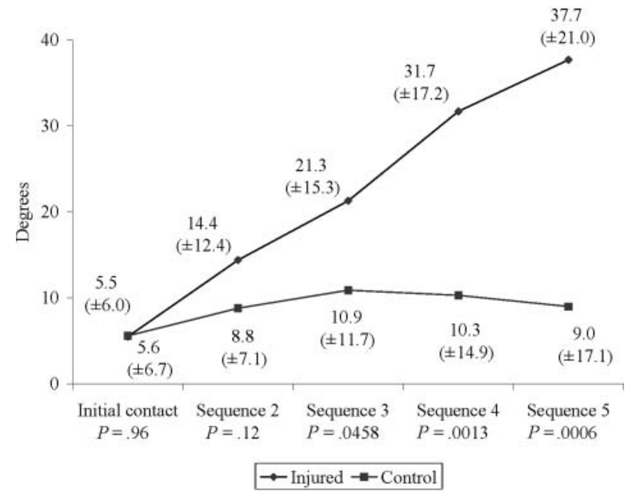

Figure 6. Coronal knee angles (mean ± SD) in subjects (injured) and controls for the 5 frames.

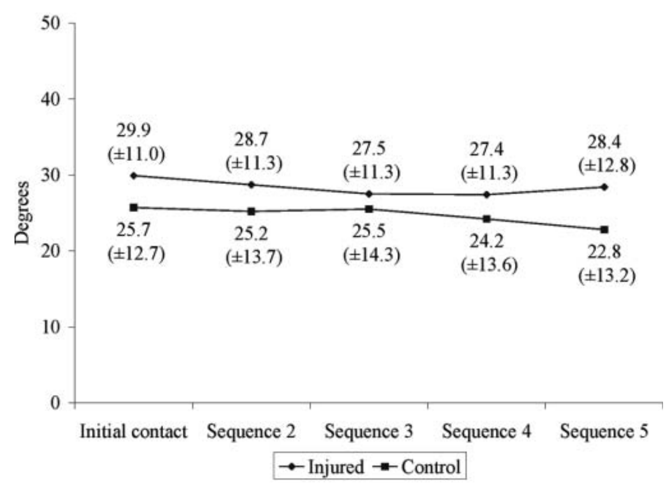

Figure 7. Coronal hip angles (mean ± SD) in subjects (injured) and controls for the 5 frames.

angle remained relatively constant (overall mean, 24.7° ± 12.6° and 28.4° ± 10.9° for subjects and controls, respectively. No significant differences in hip abduction between male and female subjects, female subjects and controls, male subjects and controls, or male and female controls were found.

DISCUSSION

Previous descriptive studies of noncontact ACL injury mechanisms have indicated that injuries occur shortly after initial contact via a landing or deceleration motion with minimal or no contact in 70% of cases.[3,4,22] We identified several new descriptive characteristics surrounding ACL injuries. These features all indicate that the athletes were performing highly competitive athletic maneuvers at the time of injury. All 29 subjects were participating in a game or competition situation at the time of injury. Although only 28% of injuries were associated with minor contact from an opposing player, 96% had an opposing player within close proximity, which may have caused an alteration in the injured players' coordination leading to a dangerous leg position. Most of the subjects (85%) were playing offense, with the ball, which may have placed additional stress on the neuromuscular system that could cause an alteration in the normal biomechanics.

Review of the injury videotapes also showed that female athletes were more frequently performing a simple deceleration motion, as opposed to the male athletes who were performing more strenuous jumping maneuvers, such as landing from a dunk or a long broad jump. Although we were unable to measure ground-reaction forces in our study, the possibility that women injure their ACL with lower impact or ground-reaction forces needs to be elucidated further.

Previous studies of ACL injuries based on videotape analysis have relied on visual inspection to determine joint positions,[4,18,22,27] a technique that has poor accuracy and precision for joint angle measurement.[17] In a study assessing the accuracy of the visual inspection technique, the mean error for knee flexion was 19°, while the standard deviation between the observers for hip flexion was 18° on average.[17] The authors used a software measurement tool to define joint position more accurately and to provide more quantitative information on injury biomechanics.

Analysis of the sagittal view joint angle measurements led to several important observations. One of the most striking differences between the subjects and controls was the position of the ankle at initial contact. The controls landed with significantly more ankle plantar flexion than did the subjects, who landed with hindfoot contact first or in a flat-footed position. In addition, the subjects' ankle angles showed relatively little change (4.1°) from the initial contact to frame 5, whereas the controls had a mean difference in ankle position of 43.8º from the first to the fifth frame. The subjects also reached a flat-footed position at an average of 1.6 frames before the controls did (1.5 and 3.1 frames, respectively).

We propose that the ankle kinematics in an injured athlete may lead to abnormal absorption of ground-reaction forces by the gastrocnemius-soleus complex. In a normal landing pattern, the gastrocnemius-soleus complex contracts to help absorb ground-reaction forces.[23] When an injured athlete lands flatfooted or with hindfoot contact first, the calf musculature may not be able to absorb the ground-reaction forces adequately, forces that then are transmitted directly to the knee. The lack of energy dissipation by the calf musculature also is supported by the lack of motion at the ankle joint in an injured athlete, as shown by our continuous frame sequences documenting that this part of the kinetic chain did not perform its function properly. In our study, subjects reached a flatfooted position at an earlier mean frame than did controls, which may have limited the amount of time for the calf muscles to contract and perform their force absorption function. In addition, as the gastrocnemius (a 2-joint muscle) contracts, it produces a flexion force on the knee, activating the normal knee absorption mechanics. In the absence of gastrocnemius contraction, the knee may abduct or internally rotate rather than flex.

Although there was a trend toward less knee flexion in subjects, especially for frames 2 and 5, the difference was not statistically significant. It is possible that our measurement technique is not sufficiently sensitive to distinguish small differences in joint angles. The reason that no significant difference between subjects and controls in terms of knee flexion angles was found in frames 2 through 5 may be because of knee valgus and rotation simulating flexion in the subjects.

The knee dynamics of the subjects were out of sync with the knee position in the controls, as evidenced by the comparison of joint angles at the first frame where the foot was 100% flat on the ground (Figure 5). The knee was significantly more flexed in the controls at the first frame where the foot was 100% flat on the ground, potentially indicating that during ACL injury, the kinetic chain of the lower extremity is malfunctioning and leading to abnormal forces at the knee. Since the foot became completely flat on the ground at an earlier frame in the injured subjects, the knee does not follow the normal flexion mechanics.

The hip angle was significantly more flexed for the first 3 frames in the subjects than in the controls. In addition, the hip was significantly more flexed for all 5 frames in our female subjects than in our female controls and for the last 2 frames for female subjects compared with male subjects. Our results concur with the findings of Krosshaug et al[18] that female injured athletes have higher hip flexion during ACL injury. The reason for the higher hip flexion angle in injured than in uninjured athletes, especially in women, has yet to be elucidated. It has been shown that increasing hip abduction/adduction stiffness (hip muscle contraction) increases the ACL injury threshold.[6] Alternatively, it is possible that a more flexed hip posture reduces the ability of the hip muscles to absorb the upper body weight or the ability of the dynamic hip stabilizers to stabilize the femur effectively.[34] Whether hip flexion in combination with a flat-footed position increases the axial forces on the knee with landing and deceleration requires additional research.

Numerous theories have been proposed to explain the etiologic factors of ACL injuries, for example, impingement of the ACL on the intercondylar notch and quadriceps-induced injury.[13] There are also many possible explanations for the increased risk of injury to female athletes, such as increased knee valgus and the hormonal effects of estrogen on the ACL.[13] On the basis of our findings, we believe that axial compressive forces or elastic instability with columnar buckling is an important component of ACL injury. Other investigators have described axial forces as the mechanism responsible for cervical spine fractures, proximal interphalangeal joint dislocations, and elbow fracture-dislocations.[2,8,15,29,31] In a porcine model, Li and coauthors[19] have also shown that axial forces significantly increase in situ forces in the ACL when combined with an anterior tibial load, compared with an isolated anterior tibial load.[7] Giffin et al[9] also showed anterior tibial translation with an axial load compared with an anterior-posterior tibial load in osteotomized cadaveric knees.

Ordinarily, the hip, knee, ankle, and foot help absorb forces during landing and deceleration activities. During the normal weight-acceptance phase of landing, the hip muscles assist in the absorption of reaction force from the upper body weight, and the ankle and foot help absorb the ground-reaction forces. When the hip, ankle, and foot segments are not effective in synergistically reducing ground-reaction forces, the leg is converted into a 2-segment column, which may be incapable of adequately absorbing the energy from the ground-reaction forces. The lack of motion at the ankle and the exaggerated hip flexion in our subjects compared with our controls may indicate that the hip and ankle joints did not absorb sufficient energy in injury situations. This theory also is supported by the joint angles at the frame (Figure 5) in which the subject's foot was completely flat on the ground.

In the coronal plane in our study, we found no significant difference in the knee abduction angle at initial contact between any of the compared groups. However, the subjects showed progressively increasing knee abduction after initial contact compared with the controls. Because we do not know the exact point of ACL injury, we are unable to state whether knee abduction contributes to the injury, is a result of the injury, or both. Our data agree with the findings of other investigators that female athletes demonstrated a greater knee abduction position ("valgus collapse") after and possibly during ACL injury than did their male counterparts.[4,18] There was also a trend in our female subjects toward more knee abduction after landing than was shown by male subjects; this finding may indicate that there is more inherent knee abduction in women during landing than in men, which concurs with the data of Hewett et al.[14]

Hewett et al[12,14] showed that a landing pattern with knee abduction is a risk for ACL injury, which may explain the higher incidence of noncontact ACL injury in women than in men. It is possible that with knee abduction, the axial forces are greater on the lateral side of the knee than on the medial side, further enhancing the lateral compressive forces and allowing for a greater internal rotation component to the injury. Additionally, with knee abduction, the ligaments on the lateral side of the knee are slack while the medial collateral ligament tightens, allowing the lateral side to shift anteriorly and rotate to release the ground-reaction force.[21] Matsumoto[21] showed that, with a valgus torque, the axis of the pivot shift is located at the medial collateral ligament. If the medial collateral ligament is taut, the movement of the medial side of the tibia is limited.[21] In contrast, there is an axial or compressive force on the lateral joint. The combination of medial and lateral compartment forces may lead to internal rotation of the tibia on the femur, which can dramatically increase the strain on the ACL.[20]

Chaudhari and Andriacchi[6] have shown the potentiating effect of knee valgus alignment on the axial theory: shifting the valgus alignment by as little as 2° can reduce the axial injury threshold of the knee by 1 body weight. This finding may explain why female athletes have a higher incidence of ACL injuries than do their male counterparts. Hewett et al[14] have shown that women tend to land with higher knee abduction moments (valgus torques), which are significant predictors of future ACL injury risk. The increased abduction moments in women compared with men indicate that the axial injury threshold is lower in women, leading to ACL injury with lower-level activities.

There were several limitations to our study. We had a relatively small sample size of videotapes, which were collected as a convenience sample, for each camera angle. These videotapes may not be representative of all noncontact ACL injury mechanisms, but the observed motions likely represent some of the most common noncontact or minimal contact mechanisms of ACL injury. We were unable to determine the exact moment at which the ACL injury occurred. However, by measuring several consecutive frames in which the knee was deforming abnormally (compared to the knee of a control) followed by the athlete falling to the ground and grabbing the knee, it is likely that the injury occurred within the 5 measured frames. In addition, although such conditions cannot be matched perfectly in different groups, even in a laboratory setting, the descriptive findings for our subjects and controls were fairly evenly matched. Because measuring knee abduction in the coronal plane does not account for rotation of the leg (internal rotation of the femur and external rotation of the tibia), our coronal knee abduction angles may not be pure knee abduction but, rather, a combination of knee abduction, internal rotation of the femur, and external rotation of the tibia. This problem may be compounded by the fact that the body may be rotating but the camera is being held still. Unfortunately, with a 2-dimensional analysis, we were unable to separate these components of motion. Future studies analyzing ACL injury videotapes where the injury was captured from more than 1 camera angle may be able to provide a more accurate 3-dimensional assessment of the various components.[16]

There were also several potential limitations in our technical analysis: possible difficulties with identifying anatomic landmarks in clothed individuals with no markers, camera angle variability that may not have captured all individuals in a perfect sagittal or coronal plane, possible microsecond differences in the timing of the first sequence picked as the foot touched the ground to the point of injury, and the limitations of 2-dimensional analysis. However, this computerized technique of angle measurements is a considerable improvement over previous descriptive studies based purely on visual estimates of joint position. Despite these limitations, to our knowledge this is the first study to analyze videotaped ACL injuries with a group of controls for comparison. Kinematic analysis with 2 or more synchronized camera views would provide more accurate data and data not yet recorded in the literature.[16]

In this study, athletes with ACL injury (subjects) showed a more flatfooted profile and a more flexed hip at the initial point of ground contact than did uninjured athletes (controls). These ankle findings may indicate that the calf muscles are not adequately dissipating the ground-reaction force, which is then transmitted directly to the knee. The clinical significance of higher degrees of hip flexion in the subjects requires additional study. This new information, as well as future data, could be incorporated into programs for the prevention of ACL injury.

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