Feature Article
Mechanisms of Anterior Cruciate Ligament Injury
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ABSTRACT
This study examined the mechanisms of anterior cruciate ligament (ACL) injury. In the first part of the study, using a comprehensive, standardized questionnaire, 89 athletes (100 knees) were interviewed about the events surrounding their ACL injury. A noncontact mechanism was reported in 71 (72%) knees and a contact injury in 28 (28%) knees; one patient was unsure if there was any contact. Most of the injuries were sustained at footstrike with the knee close to full extension. Noncontact mechanisms were classified as sudden deceleration prior to a change of direction or landing motion, while contact injuries occurred as a result of valgus collapse of the knee. Hamstring flexibility parameters revealed a statistically higher level of laxity in the injured athletes compared with a matched group of 28 controls.

In the second part of the study, videotapes of 27 separate ACL disruptions were reviewed and confirmed that most noncontact injuries occur with the knee close to extension during a sharp deceleration or landing maneuver. Because the knee is in a position to allow the extensor mechanism to strain the ACL and maximum, eccentric muscle force conditions usually apply, the quadriceps may play an important role in ACL disruption. Passive protection of the ACL by the hamstring muscles may be reduced in patients with above-average flexibility.

The anterior cruciate ligament (ACL) is one of the most commonly disrupted ligaments in the knee. Over the past 2 decades, significant strides have been made in understanding the anatomy and biomechanics of the ACL. Advances in surgical techniques and rehabilitation

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have resulted in ACL reconstruction becoming a relatively routine procedure. Although an enormous amount of information has been published on the ACL, the mechanisms and etiology of ACL injury have yet to be clearly understood.

In contrast to skiing-related ACL disruptions, little attention has been focused on the mechanism of ACL injuries in other sports. Feagin and Lambert1 described sudden deceleration, an abrupt change of direction, and a fixed foot as being key elements of an ACL injury.

McNair et al2 reported on the mechanism of ACL injury in 23 athletes. Seventy percent of the injuries involved a noncontact situation, while 30% involved contact. Ten of the 19 patients who were able to recall the events surrounding the injury described a knee flexion angle between 20° and full extension combined with internal rotation of the tibia. The authors concluded that although the mode of failure may be variable, the prominent mechanism involved a slightly flexed knee with excessive internal rotation of the tibia at footstrike.

Numerous theories have been proposed to explain the etiology of ACL injury. These can be divided into intrinsic and extrinsic factors.3 Intrinsic factors include a narrow intercondylar notch, a weak ACL, generalized physiologic laxity, hormonal effects, and malalignment of the lower extremity.
Extrinsic factors include abnormal quadriceps to hamstring interactions, altered neuromuscular control, the shoesurface interface, the playing surface, and the athlete's playing style.

This study examined the mechanisms of nonskipping ACL injuries to gain insight into which predisposing factors may be responsible for disrupting the ACL. An understanding of the nature of ACL injuries may foster appropriate preventive measures.

**Materials and Methods**

**Part One: Questionnaire Phase**

One hundred thirty-two patients (143 knees) who presented to the Duke University Sports Medicine clinic were questioned concerning the events surrounding their ACL injury. Patients with an ACL tear associated with a knee dislocation or a skiing accident were excluded from the study. Eighty-nine athletes (100 knees) were able to recall the mechanism of their ACL disruption and they formed the basis for this study.

In 92 (92%) knees, the diagnosis of a complete ACL disruption was confirmed at surgery. In 8 nonsurgically treated injuries, diagnosis was based on a positive Lachman's test. Three of these patients also had documentation of a complete ACL tear by magnetic resonance imaging (MRI).

All patients were interviewed by a physician using a standardized questionnaire. Demographic data such as age, sex, sporting activity, weather conditions, playing surface, type of footwear, and level of activity were recorded. The questionnaire concentrated on the position of the lower extremity during the injury. Data such as contact versus noncontact, knee flexion angle, position of the foot and tibia, direction knee collapsed, direction body was twisting, and other events at the time of the injury were recorded.

Anthropometric information such as hamstring flexibility and knee recurvatum also were obtained. Hamstring flexibility was recorded by asking patients how far forward they could bend with their knees locked just before the injury: fingertips to shins, fingertips to ground, knuckles ground, or palm to ground. Flexibility measurements were recorded for patients who were not in the acute postoperative period.

The recurvatum angle was recorded by centering a goniometer at the knee joint axis and aligning the arms of the goniometer with the greater trochanter and the lateral malleolus. Measurements were performed on the uninjured knee of athletes with unilateral ACL disruptions with the hip flexed 10° and repeated with the hip flexed 90°. A group of 28 age-matched athletes with no history of an ACL injury and a negative Lachman's test served as a control group.

**Part Two: Videotape Review**

In addition to the questionnaires, 27 videotapes of separate ACL disruptions were obtained from professional and collegiate teams from around the country. These videotapes were reviewed and compared with the information acquired in the questionnaires. None of the videotaped athletes were contacted to complete a questionnaire.

**Results**

**Part One: Questionnaire Phase**

Sixty-five men (72 knees) and 25 women (28 knees) participated in the questionnaire phase of the study. The average age at the time of the interview was 26 years (range: 14-48 years). The average interval from injury to interview was 3.4 years (range: 1 day to 30.3 years).

A noncontact mechanism was described in 71 (72%) knees and a contact injury was described in 28 (28%) knees; 1 patient was unsure if there was any contact. Bilateral ACL ruptures occurred in 7 men and 3 women. One patient ruptured his native ACL and his reconstructed ACL.

The most common activities at the time of injury were basketball (25%), football (21%), and soccer (21%). The majority of injuries occurred on a natural grass surface (50%), followed by an indoor hard court (25%) and a synthetic surface (8%). Weather conditions included an average temperature of 72° (range: 1°-90°) with a dry playing surface in 85 injuries and a wet surface in 14 injuries. At the time of injury, 41% of patients participated in recreational, 34% in varsity, and 23% in intramural sports.

A popping sound associated with ACL failure was described in 67 (70%) injuries. Two patients were wearing a knee brace at the time of the injury.
Only three athletes were able to temporarily continue exercising immediately after the event. A family history of an ACL injury was recorded for 11 patients, 4 of whom had bilateral ACL disruptions. The majority of athletes described the knee position as being close to full extension at the time of injury.

Hamstring flexibility revealed 46 patients (51 knees [51%]) could palm the ground, 14 (15 knees [15%]) could reach their knuckles to the ground, 28 (30 knees [30%]) could touch their fingertips to the ground, and 3 (3 knees [3%]) could only reach their lower shins (Table 1). Maximum extension in the contralateral uninjured knee of the injured patients averaged -3.96° at 10° of hip flexion and 0.04° at 90° of hip flexion.

In the control group, 6 (21%) athletes could palm the ground, 7 (25%) could reach their knuckles to the ground, 9 (32%) could touch their fingertips to the ground, and 6 (21%) could only reach their lower shins. Knee recurvatum averaged 1.57° and 9.86° at 10° and 90° of hip flexion, respectively.

These differences between the patient and control groups were statistically significant for all three measurements: bending forward (P<0.0036), recurvatum at 10° of hip flexion (P<0.001), and recurvatum at 90° of hip flexion (P<0.0001). There was no statistically significant difference in hamstring parameters between the patients who sustained an ACL injury via a noncontact versus a contact mechanism.

Injuries were classified into several different mechanisms (Table 2). In 38 ACL ruptures, the injury occurred while decelerating during or just before a change in direction.

Landing after a jumping event was another common mechanism (26 knees). At the point of impact with the ground, the athlete often contacted an irregularity in the playing surface or landed on an inverted foot. In addition, several of these events were preceded by a knee injury that may have been consistent with a partial ACL disruption.

After landing, the athletes recalled collapse of the knee into a variable amount of varus in 11 injuries, valgus in 9, and hyperextension in 6. Less commonly reported noncontact mechanisms included hyperextension in two knees, a backward fall in two disruptions, a combination of mechanisms in one patient, and an unclassifiable mechanism in one patient.

The 28 contact ACL injuries were subdivided into several mechanisms. The most common scenario was a contact blow to the lateral aspect of the leg or knee, causing valgus collapse in 13 athletes. Contact from a medial blow resulted in varus collapse in 6 patients, while an anterior blow led to a hyperextension injury in 4 and a backwards fall in 2 athletes. Three athletes suffered an ACL disruption when contacted during a change of direction. Of the 10 patients with bilateral ACL disruptions, only 2 sustained the injury via the same mechanism in both legs.

**Part Two: Videotape Analysis**

The proximity of the camera allowed analysis of 23 of the 27 injuries captured on film. The injuries occurred in 16 men and 7 women. The activities at the time of injury were football in 13 (56%), basketball in 7 (30%), soccer in 2 (9%), and volleyball in 1 (4%). The playing surfaces were an indoor hard court in 8 (35%), synthetic surface in 8 (35%), and natural grass in 7 (30%). In one athlete, a wet spot on a hard court played a part in ACL disruption. Seventeen (74%) injuries occurred in college athletes, 5 (22%) in professional athletes, and 1 (4%) in a high school athlete.

Anterior cruciate ligament mechanisms were classified as noncontact in 15 (65%) athletes and contact in 8 (35%) athletes. In the noncontact injuries, the majority of athletes were in close proximity to an opposing player, which may have disrupted the injured athlete’s coordination. Although the exact moment of ACL disruption was impossible to determine from the videotape, the position of the leg just before collapse in all of the noncontact injuries was near footstrike with the knee close to full extension.

The noncontact injuries were divided into two mechanisms (Table 2): sharp deceleration associated with 6 (40%) injuries (Figure 1) or without 4 (27%) injuries a change of direction and landing on one (3 [20%] injuries) (Figure 2) or two legs (2 [13%] injuries). None of...
Figure 2: Motion sequence of an ACL injury caused by a single-leg landing with valgus collapse.

the injuries were associated with a sharp, pivoting motion of the body around a planted leg or varus collapse of the knee.

The amount of internal and external rotation of the lower leg at the time of the injury was minimal. Valgus collapse of the knee was visualized to a variable degree in most injuries sustained via a sudden deceleration before a change in direction or a single-leg landing mechanism. There was no valgus collapse in the injuries sustained via a sharp deceleration without a change of direction or two-leg landing maneuvers. In many of the abrupt deceleration mechanisms, the hip on the injured side was in a neutral position while the trunk was leaning backwards. This tended to throw the leg anterior and out of sync with the trunk (Figure 2).

Contact ACL injuries occurred in seven football players and one soccer player. The position of the leg at the time of impact and the direction the leg collapsed were difficult to assess on the videotapes.

**DISCUSSION**

Pilot studies on the mechanism of noncontact ACL injuries have been described by a few investigators. In agreement with Feagin and Lambert, this study showed a fixed foot and deceleration are important components of an ACL injury. Additionally, the present study revealed landing frequently was reported as the event at the time of injury.

Our findings also concur with McNair et al, who reported the ratio of noncontact-to-contact ACL disruptions was close to 7:3. However, unlike the patients in the report by McNair et al who described internal tibial rotation (body rotating externally) as the most common mechanism, our patients reported a slightly higher incidence of external tibial rotation injuries (body rotating internally). Nonrotatory mechanisms also were described by many of the athletes in our study.

The relationship between the ACL and the dynamic muscular stabilizers of the knee has been studied to optimize rehabilitation of ACL-reconstructed knees. The quadriceps have been shown to be antagonists of the ACL. Contraction of the quadriceps significantly increases ACL strain in the range of 0°-45° of knee flexion.

In ACL-intact and ACL-disrupted specimens, Schoemaker et al found anterior tibial displacement resulting from a quadriceps force was greatest at 20°-25° of knee flexion. Other investigators have reported the highest amount of anterior tibial displacement occurs within 10°-30° of full extension. Because the average angle of knee flexion at the time of injury in this study was close to full extension, it is hypothesized that a vigorous, eccentric quadriceps contraction may play an important role in disruption of the ACL.

In a mechanical study on the patellofemoral forces on the knee, Nissel noted the patellar tendon-tibia angle was greatest at knee flexion angles <30°. Therefore, contraction of the quadriceps may result in significant anterior shear forces on the proximal tibia during this range of motion. Huberti et al reported the patellar tendon forces in an average adult during a maximum quadriceps contraction to be close to 2000 N. In a young, athletic individual this value may be twice as high as the average population.

Eccentric forces involve higher forces than either concentric or isometric contractions by up to 50%. Using a theoretical model, the anterior drawer force on the tibia at low angles of flexion (10°-30°) was calculated in one report to exceed 2000 N (T.J. Noonan, B. Yu, W.E. Garrett Jr, unpublished data). This value is close to the reported force necessary to disrupt the ACL.

Athletic activities such as deceleration and landing require an eccentric
contraction to resist further knee flexion. Under these conditions, muscles can exert significantly more force than isometric or concentric contractions. The ballistic deceleration mechanism is likely to involve relatively high-speed knee flexion and quadriceps lengthening. Therefore, at the time of injury, the quadriceps muscles are undergoing high-speed eccentric activation—the conditions most amenable to large force production.

Electromyographic (EMG) data have revealed a high level of quadriceps activation at heel strike, consistent with landing and deceleration activities. We are currently conducting biomechanical studies, including motion analysis and EMG data, to examine deceleration, change of direction, and landing maneuvers. In these dynamic events, the level of quadriceps activation often exceeds that seen in a maximal isometric contraction.

These factors suggest the extensor mechanism is capable of placing large anterior shear loads on the proximal tibia that may disrupt the ACL. Because injury to the ACL is extremely rare considering the large number of cutting events in sport, there must be a balance between muscle forces and mechanical loading that normally prevails. In cases in which the balance is disrupted, however, it seems possible that the force tearing the ACL may originate from the quadriceps. The imbalance may follow a slip, fall, or other uncoordinated event or unexpected condition for which the motor activation patterns did not predict the encountered condition.

The participation of women in athletics has increased dramatically in recent years. Female athletes in soccer and basketball experience a higher rate of ACL injuries compared with their male counterparts. This discrepancy may be explained by the differences in extensor mechanism anatomy between men and women.

Nisell reported the patellar tendon-tibia angle was slightly higher in women at knee flexion angles <60°. The higher patellar tendon-tibia angles in women result in greater tibiofemoral shear stresses during knee extension. Because the patellar tendon-tibia angle increases with extension, female athletes who play with a more upright style may be more prone to ACL injury.

Huston and Wojtys examined the neuromuscular response to anterior tibial translation in male and female athletes. Compared with male athletes, female athletes relied more on their quadriceps muscles and took significantly longer to generate an optimal hamstrings muscle torque. The clinical effect of estrogen and other cyclic hormones on the laxity of the ACL is currently under investigation.

The hamstring muscles act as dynamic stabilizers that exert a posterior force on the proximal tibia, protecting the ACL. Muscle forces may be divided into an active component during contraction and a passive component because of the elastic nature of the muscle. When the hip is flexed, the passive component of the muscle is typically associated with a posterior force on the tibia. In athletes with above-average hamstring flexibility, the protective ability of this muscle group may be diminished.

The data from this study indicate athletes with excess hamstring flexibility may be predisposed to ACL injury. Therefore, the quadriceps and hamstring interaction, and not just the quadriceps, may be important factors in ACL injuries. The ability to measure hamstring flexibility accurately and the interplay between the knee flexors and extensors requires further study.

The data gathered in this study may be used to help reduce the risk of ACL injury. Ettlinger et al provided ski areas with a training kit that included videotapes of ACL ski injuries followed by a training session to avoid these vulnerable positions. Skiers were taught not to lean or fall backward to avoid disruption of the ACL by a flexion and internal tibial rotation maneuver. Through this training program, the rate of serious knee sprains was reduced by 62% among trained patrollers and instructors.

A preventive strategy similar to that used in skiers may reduce the incidence of ACL injuries in contact sports. Weight-training programs that preferentially strengthen the hamstrings over the quadriceps may diminish the incidence of noncontact ACL injuries. Quadriceps muscle activity has been shown to decrease with trunk flexion, and conditioning athletes to perform with a slightly flexed trunk position may reduce the incidence of ACL injuries.

Training athletes to land from a jump on both legs may prevent many injuries.

Hewett et al reported a successfully altered muscle pattern in female athletes after 6 weeks of intense preseason jump training and conditioning. Athletes were trained to land on the balls of their feet with their knees flexed and their chest over the knees. Emphasis was placed on avoiding side-to-side motion of the knee, especially valgus, on landing. In addition, motor skills, such as the quadriceps avoidance gait, which develop normally after an ACL disruption, may be identified and added to conditioning programs.

The association between an eccentric, maximal quadriceps contraction and ACL disruption needs to be interpreted with caution. The main limitation of this study is the recall ability of the participants at an average of 3.4 years from the time of injury. In addition, the reliability of the questionnaire and the flexibility measurements was not assessed.

In addition, there were several discrepancies between the videotapes and the questionnaires. In contrast to the questionnaires, none of the videotaped injuries revealed a sharp pivoting motion around a planted leg, varus collapse of the knee, or hyperextension. This may be a result of the limited number of videotaped injuries compared with the questionnaires or more likely due to inaccuracies in the recall ability of the participants. For these reasons, the conclusions described in this report need further study.
REFERENCES


