Risk Factors for Anterior Cruciate Ligament Injury: A Review of the Literature — Part 1: Neuromuscular and Anatomic Risk

By: Helen C. Smith, Pamela Vacek, Robert J. Johnson, James R. Slauterbeck, Javad Hashemi, Sandra Shultz, and Bruce D. Beynnon

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Abstract:

Context: Injuries to the anterior cruciate ligament (ACL) of the knee are immediately debilitating and can cause long-term consequences, including the early onset of osteoarthritis. It is important to have a comprehensive understanding of all possible risk factors for ACL injury to identify individuals who are at risk for future injuries and to provide an appropriate level of counseling and programs for prevention.
Objective: This review, part 1 of a 2-part series, highlights what is known and still unknown regarding anatomic and neuromuscular risk factors for injury to the ACL from the current peer-reviewed literature.
Data Sources: Studies were identified from MEDLINE (1951–March 2011) using the MeSH terms anterior cruciate ligament, knee injury, and risk factors. The bibliographies of relevant articles and reviews were cross-referenced to complete the search.
Study Selection: Prognostic studies that utilized the case-control and prospective cohort study designs to evaluate risk factors for ACL injury were included in this review.
Results: A total of 50 case-control and prospective cohort articles were included in the review, and 30 of these studies focused on neuromuscular and anatomic risk factors.
Conclusions: Several anatomic and neuromuscular risk factors are associated with increased risk of suffering ACL injury—such as female sex and specific measures of bony geometry of the knee joint, including decreased intercondylar femoral notch size, decreased depth of concavity of the medial tibial plateau, increased slope of the tibial plateaus, and increased anterior-posterior knee laxity. These risk factors most likely act in combination to influence the risk of ACL injury; however, multivariate risk models that consider all the aforementioned risk factors in combination have not been established to explore this interaction.

Keywords: Anterior Cruciate Ligament | knee injury | risk factors

Article:

Injuries to the anterior cruciate ligament (ACL) of the knee are immediately disabling, take a significant amount of time to rehabilitate, are often associated with other concomitant articular injuries, and result in an increased risk of early onset posttraumatic osteoarthritis regardless of the treatment administered.[26] Treatment of the injury is costly and not always successful at returning patients to their preinjury activity level. Injury rates as high as 2.8 and 3.2 injuries per 10 000 athlete exposures have been reported in women's collegiate basketball and soccer.[31] Consequently, identification of factors associated with increased risk of suffering ACL injury during sport and physical activity has become a focus of musculoskeletal research. This information is needed to understand the mechanisms that produce this debilitating injury and may allow identification of those at increased risk so that targeted interventions can be implemented.

Current investigations concerning ACL injury risk focus on a range of potential factors, and the majority of these studies are based on small sample sizes and, as a result, are underpowered. Research in this field has primarily focused on a single potential risk factor in isolation. Over time it became apparent that multiple variables act in combination to influence ACL injury risk.[54] Researchers have utilized a range of measurement techniques, focused on different at-risk groups, evaluated many sports, identified an array of injury mechanisms, and utilized different study designs. Consequently, at the current point in time, it is not possible to perform a formal systematic review and meta-analysis that extract data from a combination of studies that can serve as the basis of forming consensus statements.

For the purpose of parts 1 and 2 of this literature review, prognostic studies based on prospective and case-control designs from peer-reviewed journals were reviewed and the findings summarized to provide an understanding of the information gained from the current literature. A MEDLINE electronic database search was conducted (1951 through March 2011) using the MeSH terms *anterior cruciate ligament*, *knee injury*, and *risk factors*, identifying 156 articles. Only English-language case-control and prospective cohort studies designed to identify the factors associated with increased risk of ACL injury were included, leaving 13 articles. Subsequent cross-referencing of these articles, as well as current reviews and consensus statements, was performed, yielding a total of 50 articles for inclusion in this review. Abstracts, case series studies, and descriptive studies were not included. For part 1 of this literature review, 30 articles were reviewed that focused on anatomic and neuromuscular variables. Part 2 focuses on the remaining risk factors, which include hormonal, genetic, cognitive function, previous injury, and extrinsic risk factors.

Case-control and prospective cohort studies were included in parts 1 and 2 because they can assess associations between potential risk factors and the risk of suffering ACL injury. It is important to appreciate that each design has unique strengths and weaknesses. Case-control studies are an efficient method for studying relatively rare events such as ACL injuries (in comparison with more common musculoskeletal injuries associated with sports, such as ankle sprains) because they allow researchers to accumulate a large sample size in a relatively short period, depending on the level of competition and the sport under investigation. The use of this study design can mean the difference between years and decades of data collection, particularly if one wants to establish multivariable risk models that are unique to specific groups at risk for ACL injury. However, a weakness of the case-control approach is that it may not allow potential risk factors to be studied if they are modified by the ACL injury. For example, it may not be possible to measure neuromuscular control and muscle activation variables during dynamic activities after an ACL disruption. In contrast, prospective cohort designs can be used to obtain risk factor data before the ACL injury occurs, and, consequently, the data are not modified by ACL injury; however, a weakness of this approach is that measurements must be made on extremely large cohorts to obtain a sufficient number of injuries to allow meaningful statistical analysis, and, thus, they may not be practical. Both case-control and prospective cohorts must consider the time interval between the index injury and when potential risk factor measurements are made, and this is certainly an important consideration for those outcomes that are known to change as a result of conditioning or maturation of patients or simply as a function of time. This issue can become even more challenging when the risk factor changes unpredictably over time. For example, this occurs with the study of the relationship between the risk of suffering ACL injury and the sex hormone concentrations associated with menstrual cycles that can vary dramatically in a nonreproducible manner both within and between athletes over time. It is important to distinguish (1) studies that establish links between ACL injury and a potential risk factor from (2) descriptive and case series studies that evaluate mechanisms of injury or correlate one measure to another that has theoretical implications for ACL injury risk. These latter studies were not included in this review.

Risk factors for ACL injury have been categorized as intrinsic or extrinsic.52Intrinsic variables include those inherent to the individual athlete, such as sex, hormonal milieu, genetic factors, neuromuscular and cognitive function, anatomic variables (eg, knee joint geometry, lower extremity alignment, body mass index), and previous injury to the knee or the lower extremity. Extrinsic factors are external to the athlete and may include level and type of activity, type of playing surface and environmental conditions, as well as equipment used. Part 1 of this review focuses on 2 groups of intrinsic factors: neuromuscular and anatomic.

Neuromuscular Risk Factors

Three prospective cohort studies have been published that examine the risk of suffering ACL injury in relation to measures of neuromuscular control (Table 1).[19,56,57] In a prospective study by Hewett et al, 205 adolescent female athletes who participated in soccer, basketball, and volleyball were evaluated prior to participation in their sport for “neuromuscular control” and intersegmental joint loading during a drop jump–landing task.[19] The participants who were injured (n = 9) had significantly different posture and landing biomechanics in comparison with the uninjured participants. Injured participants exhibited increased knee abduction and intersegmental abduction moment, as well as a greater ground reaction force and shorter stance time, in comparison with those who were not injured.[19] Analytic prediction of the intersegmental joint moments and forces are frequently used to characterize the dynamic biomechanical response of the knee and lower extremity during activity; however, care must be taken with the interpretation of these analytic predictions: Errors can be introduced by movement of the measurement markers attached to the soft tissues surrounding the lower extremity relative to the skeleton, and propagation of these errors through the numerical differentiation process can produce very large errors in the predicted intersegmental moments about the knee.[38]

Table 1. Neuromuscular risk factors.

Author	Study Design	N	No. of Injured Cases	Significant Risk Factors
Hewett[19]	Prospective cohort	205	9	When landing from a jump with a double-leg stance, increased knee abduction angle and intersegmental moment, increased ground reaction force, shorter stance time
Zazulak[56]	Prospective cohort	277	6	None
Zazulak[57]	Prospective cohort	277	6	Greater trunk displacement after force release

Research has also focused on “core proprioception” as a potential neuromuscular risk factor for ACL injury. Zazulak et al published 2 articles based on the same prospective cohort study that explored how various measures of core stability or proprioception are associated with ACL injury.[56,57] Collegiate athletes were tested at a baseline examination for the amount of trunk displacement after a sudden force release to measure the control of the core musculature. Athletes were followed for 3 years to determine who did and did not suffer knee injury. The parameters tested included the displacement of the trunk at maximum displacement and 150 milliseconds following release of force.[57] Active proprioceptive repositioning error was also measured as athletes were passively rotated away from an initial neutral lumbar position but then repositioned themselves in the original neutral postion.[56] The authors reported that trunk displacement was greater in ACL injured athletes (n = 6) than uninjured athletes, but there was no reported difference in active proprioceptive repoistioning error between those with ACL injury and those who were uninjured.[56,57] While it is not entirely clear how trunk displacement may relate to core proprioception, more research is needed to develop methods that mimic the common mechanism of injury in which core stability plays a role in knee injury. Core stability and proprioception do not have a well-documented set of measurement techniques that are accurate and valid for all populations. Core proprioception is defined in the literature as the body’s capacity to maintain or resume a relative position of the body after perturbation.[56] The terms *core stability* and *core proprioception*have been used interchangeably in the literature, and definitions vary between sources.[25,53] Core stability theoretically allows for production, control, and transfer of force and motion to distal segments of the kinetic chain.[56] It is hypothesized that “deficits in core neuromuscular control can cause unstable behavior and allow for a higher probability of injury throughout the kinetic chain.”[56]

Controlled laboratory studies have determined that different movement and muscle activation patterns exist between males and females; however, it is unclear how these differences are related to the risk of suffering ACL injury.[15,43] Laboratory studies have shown that females land from a jump and perform cutting and pivoting maneuvers with less knee and hip flexion, increased knee valgus, increased internal rotation of the hip coupled with increased external rotation of the tibia, and increased quadriceps muscle activation.[15] It has been hypothesized that these movement patterns increase the strain in the ACL during activity and that the large difference in knee injury incidence rates between males and females may be attributed to neuromuscular differences and resultant mechanics.[9,18] Although studies have shown that the position of the knee and the magnitude and sequence of muscle contraction can increase ACL strain values,[5,15] it is hard to correlate these movements to what occurs during activity and sport and at the time of ACL injury.

More work needs to be done to provide consistent evidence that females with increased loadings such as the valgus intersegmental moment generated about the knee during a landing task are at increased risk for ACL injury during athletic events and activity. Several outcome measurement systems that are meant to evaluate knee motion have been developed, and we anticipate that they will be applied to evaluate risk of ACL injury in the near future.[32,36] Future studies in this area need to employ longer follow-up of a larger sample to generate a sufficient number of ACL injuries for meaningful statistical analysis. Researchers should also periodically obtain repeated measures of potential risk factors on participants to rule out changes in individual knee mechanics and landing mechanics that may be produced by maturation or conditioning. When methods to measure the biomechanics of the individual are designed, it would be advantageous to mimic events in which injury occurs during practice or play so that the exact motion and reaction forces that lead up to the injury (ie, are precursors of the injury) can be evaluated. Neuromuscular control of joint biomechanics for activities thought to be associated with ACL injury (eg, planting and pivoting, a side cut maneuver, landing from a jump) has been quantified by predicting the intersegmental forces and moments generated about the tibiofemoral joint. Although these measures are considered essential for characterizing neuromuscular control, coordination, and function of the lower and upper extremity, it is important to appreciate that the use of inverse dynamic approaches to calculate the intersegmental moments about the knee rely on measurement of the foot-ground reaction forces, measurement of the positions of the limb segments, and numerical differentiation of these positions to estimate the velocities and accelerations of the limb segments during highly dynamic activities, such as transitioning from nonweightbearing to weightbearing conditions, the heel strike phase of gait, or landing from a jump. Errors in these measurements introduced by movement of the measurement markers attached to the soft tissues surrounding the lower extremity relative to the skeleton and propagation of these errors through the numerical differentiation process can produce very large errors in the predicted intersegmental moments about the knee and joints of the lower extremity. This observation has been quantified by Runge et al, who revealed that the prediction of the intersegmental moments about the knee may be in error if the number of forces and displacement measurements are not adequate and do not accurately represent skeletal biomechanics.[38]

Anatomic Risk Factors

The anatomic differences between individuals and groups, especially between males and females, are well documented.[43] Researchers hypothesize that anatomic variations between sexes may help explain, at least in part, the large difference in ACL injury incidence rates between men and women.[14] Anatomic risk factors that have been considered include various measures of knee geometry and ACL volume (Tables 2 and 3), anterior-posterior (AP) knee laxity, generalized joint laxity and static alignment of the lower extremity (Table 4), and body mass index (Table 5).

Table 2. Intercondylar notch.[a]

Author	Study Design	N	No. of Injured Cases	Significant Risk Factors
Souryal[46]	Case-control	145	95[b]	Decreased NWI
Souryal[45]	Prospective cohort	902	14	Stenotic notch, decreased NWI
LaPrade[24]	Prospective cohort	213	7	Stenotic notch, decreased NWI
Lund-Hanssen[29]	Matched case-control	46	20	Stenotic notch, decreased NWI, decreased notch opening
Schickendantz[39]	Case-control	91	61[c]	None
Shelbourne[41]	Prospective cohort	714	27[d]	Narrower notch width
Ireland[21]	Case-control	294	108	Decreased notch width, NWI, A-shaped notch
Lombardo[27]	Case-control	305	14	None
Uhorchak[49]	Prospective cohort	895	24	Decreased notch width
Domzalski[12]	Case-control	90	46	Decreased notch width
Everhart[13]	Matched case-control	54	27	Increased ridge thickness of anterior notch, notch stenosis
Chaudhari[11]	Matched case-control	54	27	Decreased anterior cruciate ligament volume

[a]NWI, notch width index.
[b]Unilateral, 50; bilateral, 45.
[c]Unilateral, 30; bilateral, 31.
[d]Contralateral injury.

Table 3. Tibial geometry.

Author	Study Design	N	No. of Injured Cases	Significant Risk Factors
Meister[30]	Matched case-control	88	49	None
Hashemi[17]	Case-control	104	49	Increased lateral and medial posterior tibial plateau slopes, decreased medial tibial plateau depth
Todd[48]	Case-control	319	140	Increased posterior tibial plateau slope in females
Stijak[47]	Matched case-control	66	33	Increased posterior lateral tibial plateau slope
Vyas[51]	Case-control	39	16	Increased posterior medial tibial plateau slope
Bisson[6]	Case-control	80	40	Increased medial and lateral tibial plateau length (anterior-posterior) increased lateral posterior tibial plateau slope in males
Simon[44]	Matched case-control	54	27	Increased posterior tibial plateau slope, decreased intercondylar notch width and volume
Khan[22]	Case-control	124	73	Increased lateral posterior tibial plateau slope, shallow medial tibial depth in females
Hudek[20]	Matched case-control	110	55	Increased meniscal slope

Table 4. Laxity and alignment risk factors.

Author	Study Design	N	No. of Injured Cases	Significant Risk Factors
Uhorchak[49]	Prospective cohort	895	24	Increased generalized joint laxity, increased anterior-posterior knee laxity in females
Loudon[28]	Matched case-control	40	20	Increased knee recurvatum, increased navicular drop, increased subtalar joint pronation
Vauhnik[50]	Prospective cohort	520	11	Increased passive knee extension
Kramer[23]	Case-control	66	33	Increased general joint laxity, increased genu recurvatum, decreased iliotibial band flexibility
Ramesh[37]	Matched case-control	234	169	Increased knee hyperextension, increased generalized joint laxity
Woodford-Rogers[55]	Matched case-control	44	22	Increased anterior knee laxity, increased navicular drop
Myer[33]	Matched case-control	95	19	Increased knee hyperextension, increase in side-to-side differences

Table 5. Body mass index.

Author	Study Design	N	No. of Injured Cases	Significant Risk Factor
Uhorchak[49]	Prospective cohort	895	24	Increased body mass index in females

Knee Geometry: Intercondylar Notch

Studies that have focused on determining if differences in the femoral intercondylar notch width correlate with differences in ACL injury risk vary substantially in their measurement techniques. These techniques are used to measure different aspects of the geometry of the intercondylar notch. These measurements are expressed as different indices with different statistical analyses; consequently, the findings from these studies are difficult to compare. However, some general observations can be made using the studies that have focused on intercondylar notch width in isolation and those that have included multivariable risk factor studies. The ACL is located in the intercondylar notch of the femur; researchers speculate that it may become impinged against the notch at specific knee positions and at the limits of joint motion.[15] At this point it is difficult to assess whether the aspect of the joint that should be considered is the size and geometry of the notch itself, the volume of the ACL, or some combination that characterizes both structures.

In a case-control study, Souryal et al attempted to determine if intercondylar notch width was a predisposing factor for bilateral ACL tears.[46] Notch width index (NWI) was measured using tunnel view radiographs. The NWI was identifed as the ratio of the width of the intercondylar notch to the width of the distal femur at the level of the popliteal groove. The authors reported that the NWI was significantly smaller in the group that suffered bilateral ruptures of their ACL when compared with the group with normal knees and that which suffered unilateral ACL ruptures. There was no significant difference in NWI between the normal knee group and unilateral ACL tear group. Women had, on average, a smaller NWI than men.[46]

In a subsequent prospective cohort study by the same group, the authors reported a larger NWI in men compared with women and that the athletes who suffered ACL injuries had significantly more *notch stenosis*, defined as an NWI less than 1 standard deviation of the mean compared with uninjured athletes. The athletes with ACL injuries had significantly lower NWI than noninjured athletes.[45] This finding was corroborated by 2 prospective studies in which radiographic-based measurements were used to show a positive correlation between notch stenosis, defined as NWI < .20, and ACL injury,[24] and a similar stenotic notch, defined as width < 17 mm, and for which an increased risk of ACL injury was found.[29] In a case-control study by Schickendantz et al, however, no significant differences were found among bilateral ACL, unilateral ACL, or uninjured groups when comparing measures of NWI or notch width.[39]

In a prospective cohort study by Shelbourne et al, patients who underwent ACL reconstructions had notch width measured intraoperatively.[41] The authors reported that with patient height and weight as covariates, women had smaller intercondylar notches than men. Patients were followed for contralateral ACL and/or ACL graft tears, and those with a narrow notch (< 15 mm) had an increased risk of suffering an ACL tear in their contralateral knee. When graft tears alone were evaluated, the sex difference in the ACL tear rate was eliminated. From this finding, the authors suggest that the notch size may not be responsible for ACL injury risk but that the size of the ACL itself may be the underlying cause.[41]

A retrospective case-control study was performed by Ireland et al using radiographic-based measurement techniques.[21] NWI was measured, and the notch was characterized as being A-shaped or non-A-shaped. The authors reported that a greater proportion of women had A-shaped notches than men and that injured patients had a significantly smaller notch and NWI than uninjured patients regardless of sex. An interesting finding in this study was that when changes in knee angle were made while radiographs were taken, the resulting notch width measurement was significantly affected. This finding was corroborated in a cadaveric study by Anderson et al that showed statistically significant differences in caliper measurements of notch width compared with planar radiographic measurements.[1] This study highlighted the inability of researchers to accurately identify the anterior outlet of the intercondylar notch on planar radiographs. These are limitations associated with all planar radiographic-based measurements, and all future studies using radiographs should obtain measurements in an accurate and reliable manner using 3-dimensional techniques.

Lombardo et al performed a case-control study on National Basketball Association players to determine if differences in NWI existed between ACL-injured and noninjured players.[27] No significant difference was found.

In a large prospective study by Uhorchak et al, 895 cadets at the United States Military Academy had a selection of potential risk factors measured prior to exposure to sport and military training, and the cadets were then followed for the duration of their undergraduate careers to determine who went on to suffer an ACL injury or remained uninjured.[49] Radiographic measures of notch width and NWI were obtained, and 2 new indices were calculated: the eminence width index (eminence width/tibial width) and notch width/eminence width index. These were used to estimate size of the ACL in relation to the size of the tibia and the size of the ACL in relation to the notch width. Small intercondylar notch width (low values for all 4 indices) was associated with an increase risk of ACL injury for men and women considered in isolation and when grouped.[49]

As magnetic resonance imaging (MRI) techniques become more accessible and easier to utilize, many researchers have moved from plain radiographic to magnetic resonance–based approaches for measuring knee geometry. For example, NWI has been measured using MRI by Domzalski et al. This case-control study found that young ACL-injured patients (11.5-17 years old) had a smaller NWI than uninjured matched controls.[12] Everhart et al used MRI in a case-control study to measure the morphometry of the intercondylar notch. The researchers identified a bony ridge on the femoral condyle located on the anterior outlet of the notch; an increase in thickness of this ridge was associated with increased risk of ACL injury. Notch stenosis measured at the anterior outlet of the notch was also correlated with risk of suffering ACL injury in this study.[13] ACL volume was measured by Chaudhari et al in injured patients and matched controls with MRI (with the volume of the ACL in the contralateral, uninjured knee being used to represent the volume of the ACL from the injured side prior to the injury). The contralateral ACL volume of the injured patients was significantly smaller than the ACL volume from the uninjured controls.[11]

Overall, a majority of studies have found a relationship between notch width or NWI and risk of suffering an ACL injury. As intercondylar notch width decreases, an increase in ACL injury risk is observed.[*]

Although the following studies were not included in the review, it is important to point out that the intercondylar notch has been found to be smaller in women compared with men and is related to ACL volume.[2,7,8,10] In another descriptive study, significant differences in notch width were reported between African American men and white men, as well as between African American women and white women.[42] Overall, African Americans had larger intercondylar notches. This observation introduces the hypothesis that incidence rate of ACL injury may be different among those of different racial backgrounds.[42] Consequently, it may be necessary to control for the effects of sex and racial/ethnic backgrounds when one assesses knee geometry in relation to ACL injury risk.

Knee Geometry: Tibial Slope

A promising risk factor for ACL injury has been identified using MRI measures of bony geometry of the tibial plateau. The geometry of the tibiofemoral joint has an important role in controlling transmission of the large compression and shear intersegmental forces across the knee, specifically the location and orientation of the contact forces about the medial and lateral aspects of the tibial plateau, and the strain placed upon the ACL during weightbearing activity.[16] Bony geometry characteristics explored thus far include the depth of the concave surface of the medial tibial plateau and the posterior-inferior-directed slopes of the medial and lateral plateaus of the tibia. For each plateau, a posterior-inferior-directed slope is identified by the anterior elevation of the tibial plateau being higher than the posterior elevation. Researchers believe that in certain situations the compressive joint reaction force that acts on a posterior-inferior-directed slope of the tibial plateau can have an anterior-directed shear force component that acts on the tibia, and this force combines with the other sources of anterior-directed forces to produce the net intersegmental force that acts on the tibia. If the magnitude of the net anterior-directed intersegmental force exceeds the failure strength of the ACL, then an injury occurs.[16] These characteristics of the bony geometry of the knee are considered important because they may act in combination to influence injury risk. For example, an increase in posterior-inferior-directed slopes of the tibial plateaus combines with decreased medial tibial depth to result in increased risk for ACL injury.[16,17] Overall geometry of the tibial plateau, such as the depth of concavity of the plateau as characterized by the medial tibial depth, may be important because it defines the constraint imparted to the knee by the conformity (or lack thereof) of its articular surfaces. These simple geometric characteristics may further our understanding of how the forces transmitted across the knee influence injury risk so that we can begin to predict how individual knee joints will behave under the stress of activity.[17]

Although an early radiographic case-control study showed no influence of tibial plateau slope on ACL injury,[30] there have been 8 studies to date that have correlated measures of bony tibial geometry with the risk of suffering ACL injury.[6,17,22,44,47,48,51] One study has been published on the influence of the shape of the meniscus in the knee joint on ACL injury risk.[20] Hashemi et al performed a case-control study that used MRI to measure the proximal aspect of the tibial plateau and found that female ACL-injured cases had increased posterior-inferior-directed lateral tibial plateau slope and shallower medial tibial plateau depth compared with uninjured controls.[17] Male cases had increased posterior-inferior-directed medial and lateral tibial plateau slopes and shallower medial tibial plateau depth than the uninjured controls.[17] Plain film radiographs were used in a separate study of a military population.[48] Female patients who suffered an ACL injury had a greater medial posterior-inferior tibial plateau slopes than matched controls. These findings were corroborated on the lateral tibia by a separate group that used MRI and radiographs to measure tibial plateau slope in ACL-injured cases and matched controls.[47] Injured cases had greater lateral posterior-inferior tibial plateau slopes than their matched controls.

Vyas et al studied adolescents between the ages of 12 and 17 years and found that ACL-injured cases had greater posterior-inferior-directed medial tibial plateau slopes than uninjured controls. There was no difference in NWI between groups and no differences between male and female groups for measures of tibial slope or NWI.[51] This study may indicate that more work needs to be completed in the young age group and that tibial geometry may be different in children in comparison with adults. Hudek et al, in a matched case-control study with MRI measures of tibial slope, found no statistically significant relationship between the posterior-inferior-directed tibial plateau slope and ACL injury. However, there was an increase in the slope of the lateral menisci (anterior to posterior) associated with increased injury. Females had greater posterior-inferior-directed tibial plateau slopes on the lateral and medial sides in comparison to males.[20]

Several studies have attempted to examine other measures of knee geometry as risk factors for ACL injury. Bisson et al evaluated ACL-injured cases and matched control knees with MRI for sagittal and axial femoral condyle AP length and tibial AP length.[6] No differences were found between female ACL-injured cases and uninjured controls, but male cases, compared with male controls, had longer AP medial and lateral tibial plateaus as well as increased posterior-inferior slope of the lateral tibial plateau. Simon et al measured ACL volume, tibial plateau slope, and notch geometry in another MRI case-control study.[44] Increased posterior slope of the lateral tibial plateau and smaller notch dimensions were found in injured cases versus controls. Khan et al[22] also found that ACL-injured patients had steeper posterior-inferior-directed lateral tibial slopes compared with uninjured cases and that female cases had shallower medial tibial plateau depth than uninjured women. These results corroborate some of the findings of Hashemi et al in 2010,[17] even though this group utilized slightly different measurement methods.

Evidence is emerging for the influence of bony tibial geometry on the risk of suffering ACL injury either in isolation or in combination with other risk factors. Our review found that no study has examined the effect of the articular cartilage surface geometry on ACL injury risk. This may be important to consider because contact stress is transmitted between the cartilage surfaces of the tibiofemoral joint, which have a different profile than the underlying bony geometry. Furthermore, knee geometry may very well have potential to influence the effects of other risk factors, including the intersegmental knee abduction moment, other measures of "knee valgus," and lower extremity alignment.

Generalized Laxity, Knee Joint Laxity, and Static Alignment

Several studies have focused on generalized and knee joint laxity as risk factors for ACL injury in isolation and in combination with other factors, such as static alignment of the lower extremity (Table 4).[†,34] Females have greater knee and general joint laxity than males.[43] The use of the KT-1000 arthrometer to measure anterior-posterior knee joint laxity is a popular technique and specific to the ACL. Increased generalized joint laxity4 is a risk factor for ACL injury in both males and females, and increased AP knee joint laxity (KT-1000) is associated with increased risk of injury.[4,49,55] Injured patients also displayed increased navicular drop when compared with controls.[55]

Two case-control studies and 1 prospective cohort study reported that increased passive knee extension was associated with increased risk of ACL injury.[28,37,50]Loudon et al also found that increased subtalar joint pronation and navicular drop were associated with increased risk of ACL injury.[28] Ramesh et al found that generalized joint laxity was also associated with an increase in ACL injuries.[37]Kramer et al found that ACL injury was associated with increased generalized joint laxity, increased knee extension, and increased illiotibial band flexibility.[23] In a recent case-control study, Myer et al reported that increased knee hyperextension and side-to-side differences in AP knee laxity as measured with the KT-1000 was associated with ACL injury in females (n = 19).[33]

These studies arrive at the same finding: Increased knee laxity in an otherwise normal knee is associated with an increase in ACL injury risk.

Body Mass Index

Higher-than-average body mass index is an ACL injury risk factor for women in the United States Military Academy cadet population (Table 5).[49] This finding was not observed among the male cadets.

Multivariable Risk Factor Analysis

To date, 2 previously mentioned studies have examined the risk of ACL injury for combinations of risk factors by developing multivariable models.[17,49] These models have focused exclusively on anatomic variables. In the prospective cohort study by Uhorchak et al, relative risk ratios associated with having 1 or more risk factors ranged from 1.0 to 37.7, depending on the factors considered. For example, the relative risk of ACL injury for the combination of decreased notch width, increased body mass index, and increased AP knee laxity values was 21.3 times that of controls, while the relative risk of each factor considered alone was 3.8, 2.0, and 2.6, respectively. The models that predicted ACL injury were different for males and females.[49]

Likewise, Hashemi et al evaluated multiple measures of the bony geometry of the tibial plateau and considered how they were associated with risk of ACL injury in isolation and combination.17 When medial tibial depth decreased by 1 mm in isolation, the odds ratio (OR) associated with ACL injury risk was 3.03. Likewise, the OR with a 1-degree increase in lateral tibial plateau slope (LTS) was 1.17. However, when the 1-mm decrease in medial tibial depth was combined with a 1-degree increase in LTS, the OR associated with each was multiplied to produce an OR of 3.58. The logistic regression models that predicted ACL injury were different for males and females. For females, decreased medial tibial depth and increased LTS combined to produce an OR of 3.58. For males, decreased medial tibial depth, increased LTS, and increased medial tibial slope resulted in an OR of 4.18. These findings highlight the fact that different variables may act in combination to increase the risk of injury among groups: males and females. New risk factors should be evaluated in isolation as well as in combination with other factors in an effort to develop comprehensive risk models for groups at risk.

Conclusion

Anatomic features, such as a decrease in femoral notch width, a decrease in the depth of concavity of the medial tibial plateau, and an increase in the posterior-inferior-directed slope of the tibial plateau, act in combination to increase the risk of suffering an ACL injury. More research needs to be done with regard to the effects of knee geometry on the risk of suffering ACL injury in terms of risk at different stages of growth and skeletal development.

Several potential neuromuscular risk factors deserve further investigation. It is very probable that multiple risk factors act in combination to influence injury risk, and these combinations of factors may be unique to certain groups (eg, males vs females, high school vs college, soccer vs basketball).[3]

Investigations on neuromuscular factors reported to date do not provide a complete understanding of ACL injury risk. Through a comprehensive understanding of all possible risk factors, intrinsic and extrinsic, modifiable and nonmodifiable, we can begin to identify individuals at risk for future injuries and reinjury and provide an appropriate level of counseling and programs for prevention. As with all studies of injuries or diseases that are relatively rare, future studies on ACL injuries must examine a large population over a long period to produce enough injuries for meaningful statistical analysis.[35] Several studies that were reviewed suffered from very small sample sizes, which limit the conclusions that can be drawn. Future research efforts should also use consistent measurement techniques and tools to allow subsequent extraction and pooling of data for systematic reviews and meta-analyses. Replication of current studies is needed to rule out spurious associations and establish putative risk factors for ACL injury.[40] The ultimate goal of research on ACL injury should concentrate on creating comprehensive, clinically applicable risk models that can identify who is at increased risk of suffering the injury and provide direction for the development of prevention techniques as well as appropriate health care and counseling for those who may be at increased risk of suffering multiple injuries.

Footnotes

[*] References [11, 12, 21,24,29, 41, 45, 46, 49].

[†] References [23, 28, 33,37, 49, 50,55].

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