Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors, and prevention programs

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Review

Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors, and prevention programs

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Abstract

Anterior cruciate ligament (ACL) injuries are common in soccer. Understanding ACL loading mechanisms and risk factors for ACL injury is critical for designing effective prevention programs. The purpose of this review is to summarize the relevant literature on ACL loading mechanisms, ACL injury risk factors, and current ACL injury prevention programs for soccer players. Literature has shown that tibial anterior translation due to shear force at the proximal end of tibia is the primary ACL loading mechanism. No evidence has been found showing that knee valgus moment is the primary ACL loading mechanism. ACL loading mechanisms are largely ignored in previous studies on risk factors for ACL injury. Identified risk factors have little connections to ACL loading mechanisms. The results of studies on ACL injury prevention programs for soccer players are inconsistent. Current ACL injury prevention programs for soccer players are clinically ineffective due to low compliance. Future studies are urgently needed to identify risk factors for ACL injury in soccer that is connected to ACL loading mechanisms, and have cause-and-effect relationships with injury rate, and develop new prevention programs to improve compliance.

Keywords: ACL injuries; Biomechanics; Injury prevention; Soccer

1. Introduction

Soccer is the most popular sport in the world.[1] Playing soccer can improve musculoskeletal, metabolic, and cardiovascular functions.[2] However, soccer is one of the sports that have the highest risk of anterior cruciate ligament (ACL) injury.[3,4] The incidence rates of ACL injury in soccer range 0.15%–3.67% per person per year and 0.07–1.08 per 1,000 sports exposures across various age and competition levels.[5,6] Female soccer players are 2–3 times more likely to suffer ACL injuries compared to male soccer players.[5,7] The majority of ACL injuries occur without external contact to the knee joint.[4,8,9,9–15]

ACL injuries have brought financial burden to society, and caused devastating consequences to patients' quality of life. Based on an estimated 200,000 cases of ACL tears in US each year, annual cost of ACL injury is estimated to be US$4 billion for surgical treatment alone.[16] The lifetime financial burden of these injuries to society is estimated to be US$7.6 billion annually when treated with ACL reconstruction and US$17.7 billion when treated with rehabilitation.[17] Even with ACL reconstructions, individuals after reconstructed ACLs usually have abnormal strength, proprioception, balance, and neuromuscular control patterns[18] as well as increased risks for re-injury.[19–21] Many of these individuals are not able to return to their pre-injury level of activity.[22] Fifty-nine to 70% of these individuals would develop radiographically diagnosed knee osteoarthritis; 16%–19% would have symptomatic knee osteoarthritis over their lifetime, and 13%–15% would need total knee arthroplasty.[17] Tremendous research and clinical

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efforts have been made in the last two decades to prevent ACL injuries and improve the rehabilitation after ACL reconstruction surgeries,[23–25] however ACL injury rates have not been reduced.[10,26,27]

van Mechelen et al.[28] proposed a sequence for preventing sports injuries. In this sequence, prevention of sports injury should follow four steps: (1) descriptions of the extent of injuries, (2) understanding of injury mechanisms and identification of risk factors, (3) development of injury prevention strategies, and (4) evaluation injury prevention strategy. The problem of ACL injury has been well described, however, the injury mechanisms and risk factors for ACL injury are still not well understood and identified. Consequently current ACL injury prevention programs have limitations that prevent them from being effective. Therefore, the purpose of this review is to summarize the relevant literature on ACL loading mechanisms, ACL injury risk factors, and current ACL injury prevention programs for soccer players. We hope this review will contribute to the development of future ACL injury prevention programs in soccer as well as in other sports.

2. Loading mechanisms

The ACL is a primary restraint to anterior translation of the tibia relative to the femur.[29] *In vitro* studies demonstrated that an anterior shear force applied on the tibia was the primary ACL loading mechanism.[30,31] The magnitude of anterior shear force applied on the tibia and its effect on ACL loading are largely affected by the posterior ground reaction force and knee flexion angle during a movement. The posterior ground reaction force on the foot during a movement creates a flexion moment at the knee that needs to be balanced by an extension moment at the knee. The quadriceps is the primary generator of knee extension moments. While generating knee moments, the quadriceps applies an anterior shear force at the proximal end of the tibia that is a primary cause of anterior tibial translation and ACL loading mechanism.[30,31] A previous study demonstrated that the peak impact posterior ground reaction force was significantly correlated to the peak impact knee extension moment and proximal tibial anterior shear force during the landing of a stop-jump task.[32]

Knee flexion angle affects ACL loading through its relationships with patella tendon-tibia shaft angle and ACL elevation angle.[33–35] Studies showed that ACL loading decreased when knee flexion angles increased.[30,36] Taylor et al.[37] recently quantified *in vivo* ACL length during a landing task using a combined fluoroscopic, magnetic resonance imaging (MRI), and videographic technique. They found that knee flexion angle and ACL length were negatively correlated, and that the peak ACL length actually occurred prior to landing when the knee flexion angle was minimal. Taylor et al.[38] also found that knee flexion angles explained 61% of the variance in ACL length, and that peak ACL length occurred in mid-stance during walking when the knee was close to full extension. Using the same technique, Brown et al.[39] found that landing with an increased initial knee flexion angle decreased peak ACL length during both pre-landing and landing phases of a drop vertical jump task. Kim et al.[40] recently estimated knee kinematics at the time of ACL injury for eight patients following ACL injuries through reconstruction of the relative positions of the femur and tibia at the time of ACL injury by maximizing the contact of bone bruise areas between the femur and tibia in MRI. Their results showed a mean tibial anterior translation of 22 mm, a mean knee flexion angle of 12°, and a mean knee valgus angle of 5° at the time of ACL injury. These findings clearly demonstrate that anterior translation of the tibia relative to the femur is the primary mechanism of ACL injury, and that a small knee flexion angle is responsible for an increased anterior shear force at the knee and thus anterior translation of the tibia relative to the femur.

The ACL can also be loaded by a compressive force along the longitudinal axis of the tibia through a posterior tilted tibial plateau.[41,42] With the presence of a posterior tibial plateau slope, a compressive force can generate an anterior shear force to cause the tibia to translate anteriorly and load the ACL.[41,42] An *in vitro* study showed that anterior translation of the tibia relative to the femur increased when the posterior titled tibial plateau slope increased from 8.8° to 13.2° under a 200 N compressive force loading.[43] An *in vivo* study showed that female patients with ACL injuries had significantly greater posterior tibia plateau slopes than the uninjured individuals.[44] These results provide a plausible explanation of the mechanism of ACL injury occurring in vertical landing tasks in which the external forces on the lower extremity are mainly in the vertical direction.

Knee "valgus collapse" was repeatedly proposed to be the major ACL injury mechanism especially in women based on the observation of ACL injury video records.[9,45] Quatman and Hewett[45] proposed sex-specific mechanism of ACL injuries. The investigators indicated that a primarily "sagittal plane" ACL injury mechanism might be correct for male athletes, but female athletes sustained ACL injuries by a predominantly "valgus collapse" mechanism. However, evidences from quantitative studies do not support "valgus collapse" as the injury mechanism for either males or females. *In vitro* studies demonstrated that, although knee valgus, varus, and internal rotation moments affected ACL loading, their effects were significant only when an anterior shear force was present at the knee.[30,31] A recent *in vivo* study demonstrated that the knee valgus collapse did not increase ACL length when the knee was in a flexion position.[46] Also, studies demonstrated that medial collateral ligament was the primary structure resisting knee valgus moment in an intact knee, and that a pure valgus moment could not rupture ACL until the medial collateral ligament was completely ruptured.[47–49] Only 6% patients who had ACL injuries completely ruptured their medial collateral ligaments.[50] Further, an *in vitro* study found that the knee valgus motion significantly increased only after the ACL had been injured,[42] which indicated that the increased knee valgus motion observed in injury video records was likely a consequence instead of a cause of ACL injuries.

Current literature suggests that anterior translation of the tibia relative to the femur is the primary mechanism of ACL loading. Increased anterior shear forces at the knee due to a small knee flexion angle and increased compression forces on a posteriorly tilted tibial plateau are primary causes of anterior translation of the tibia relative to the femur. Although knee valgus/varus and internal rotation moments affect ACL loading when combined with significant anterior shear forces at the knee, current literature does not support them as primary ACL loading mechanisms relevant to ACL injuries. Future studies are encouraged to employ non-invasive methods[37] to quantify *in vivo* ACL loading during athletics tasks to determine ACL loading mechanisms under the loading that is close to cause ACL injuries.

3. Risk factors

Most ACL injuries occur during athletic tasks without external contact to the knee joint.[4,8–15] The non-contact nature suggests that these injuries are likely caused by abnormal movement patterns which might be modified through training. Understanding the risky movement patterns for non-contact ACL injuries can provide valuable information for developing training strategies. Significant efforts have been made to identify risk factors for non-contact ACL injury using a variety of methods in the last two decades. One method to identify movement characteristics in injury events is through the analysis of video records of ACL injury cases. Cochrane et al.[12] analyzed video records of 34 ACL injury cases in Australian football. They found that most of the injuries occurred during sidestepping or landing tasks when the knee flexion angle was less than 30°, and that 47% of the non-contact injuries had increased knee valgus motion and 42% had increased internal tibial rotation.

Krosshaug et al.[9] analyzed video records of 39 ACL injury cases in basketball. They estimated the time of injury being 17−50 ms after initial foot contact with the ground. Both males and females demonstrated small knee flexion angles at initial foot contact with the ground (<15°) and 50 ms after (<28°). This study also found that females had greater knee flexion angles than males did, and that females were more likely to have a valgus collapse than males did. Boden et al.[14] analyzed video records at a side view of 12 ACL injury cases and video records approximately at a front view of 17 ACL injury cases. They found that injured individuals had an increased rate of landing with flatfoot or rearfoot, increased knee abduction, and increased hip flexion compared to non-injured controls in similar video records. Sheehan et al.[13] analyzed video records of 20 ACL injury cases occurred in single-legged landing tasks and 20 non-injured control cases. They found that the distances from center of mass to base of support and the angles between thigh and vertical axis were increased and that the angles between trunk and vertical axis were decreased in ACL injury cases compared to non-injured control cases. These studies were generally qualitative in nature. The video images used in these studies were not recorded for quantitative movement analyses with little control of image quality and no calibration was performed. Joint angles estimated from these two-dimensional (2D) video records were projections of angles between segment longitudinal axes on the view plane, which contained significant errors[51–53] and made the validity of the results questionable.

Recognizing the significant limitations in 2D video analysis of injury events, Krosshaug and Bahr[54] developed a model based manual image-matching technique in attempt to reconstruct three-dimensional (3D) movements in injury events from single or multiple uncalibrated cameras. Koga et al.[55] analyzed movement characteristics of 10 ACL injury cases in female team handball and basketball using the model based manual image-matching technique. They estimated that injuries occurred about 40 ms after initial foot contact with the ground. Knee flexion and knee valgus increased during the first 40 ms after the initial foot contact with the ground, and that the knee was externally rotated at initial foot contact with the ground, and internally rotated during the first 40 ms after the initial foot contact. The investigators concluded that the valgus motion coupled with internal tibial rotation under low knee flexion appeared to be important risk factors for ACL injury.[55] However the measurement errors of the model-based manual image-matching technique were up to 11° in knee flexion angle, 13° in knee internal/external rotation angle, and 5° in knee varus/valgus angle.[54] These significant measurement errors minimized the validity of this study.

Another method to identify risk factors for ACL injury is to determine associations of injury risk factors with pre-injury movement characteristics through prospective cohort studies. In a prospective cohort study,[56] 205 adolescent soccer, basketball, and volleyball players were screened for lower extremity biomechanics in a drop landing task, and subsequently followed for 13 months. Nine ACL injuries (7 in soccer and 2 in basketball) occurred. Compared to the non-injured players, the injured-players had increased knee abduction angles at initial contact, maximum knee abduction angles, maximum external knee abduction moments, peak vertical ground reaction forces, maximum external hip flexion moments, and side-to-side knee abduction moment differences during landing, and decreased maximum knee flexion angles and stance time. Statistical analysis demonstrated that the knee abduction moment was the most sensitive factor to predict ACL injury with 75% specificity and 78% sensitivity. This was the first prospective cohort study in an attempt to screen jump-landing mechanics to identify biomechanical risk factors for ACL injury. However a small number of injuries, the late occurrence of the maximum knee valgus moment during the stance phase, a lack of horizontal deceleration in the testing task, and a lack of consideration of ACL loading mechanisms were identified as limitations of this study.[23] Also a lack of cause-and-effect relationship between identified risk factors and the injury risk is another significant limitation of this type of prospective cohort study.

Another study to prospectively identify risk factors for ACL injury was performed at three US military academies for 5 years.[57] A total of 6,124 cadets were screened for lower extremity biomechanics in a simulated stop-jump task. Ninety-eight cadets had ACL injuries after the screening. Compared to the non-injured cadets, the injured cadets had increased

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knee abduction at initial contact, increased maximum hip flexion, increased hip adduction at initial contact, and increased external hip rotation at initial contact during landing. This study found that male cadets had a similar ACL injury rate as female cadets. The discrepancy in gender bias in ACL injury rates between the cadet population and other athletic populations indicates that the risk factors identified in the cadet population may not be generalizable to other athletic populations. A large sample size was obtained in this study, however similar to the previous study,[56] a lack of consideration of ACL loading mechanisms and a lack of cause-and-effect relationship between identified risk factors and injury risk are significant limitations of this study.

Smith et al.[58] conducted a large-scale prospective study to identify biomechanical risk factors. They used a semi-quantitative method called Landing Error Scoring System (LESS)[59] as a lower extremity movement evaluation tool. A total of 2,021 male and 1,855 female college and high school athletes from various sports were screened for lower extremity movement patterns in a jump-landing-jump task and subsequently followed for three years. The LESS scores were compared between 28 ACL injured athletes and 64 matched controls. No significant difference in LESS score was found between the injured and non-injured groups. There are at least two possible explanations for the findings of this study: (1) the LESS could not differentiate lower extremity movement patterns between injured and non-injured groups, or (2) the movement patterns the LESS screened were not risk factors for ACL injury.

Goetschius et al.[60] predicted the probability of high knee abduction moments for the female athletes in the study by Smith et al.[58] The knee abduction moments were estimated from 2D knee valgus motion, knee flexion range of motion, body mass, tibia length, and quadriceps-to-hamstring strength ratio.[61] No significant difference was observed in the predicted probabilities between 20 injured athletes and 45 controls. The results suggested that maximum knee abduction moment was not a risk factor for ACL injury in this population.

Risk factors for non-contact ACL injury are still largely unknown despite significant research efforts in last two decades. The identified risk factors were inconsistent among studies, and lacked connections with ACL loading mechanisms and cause-and-effect relationships with the risk of the injury.[25,62] These limitations in the current literature on the risk factors for ACL injury are due to the inherent limitations of the research methods. In the future, 3D motion analysis methods that can be applied to accurately quantify motion during injury events are needed. A conclusion regarding injury mechanisms can only be drawn when the analysis are reliable. Studies with a better research design and consideration of ACL loading mechanisms are needed to identify ACL injury risk factors.

4. Prevention programs

Although the risk factors for ACL injuries are still unclear, many injury prevention programs have been developed for soccer players as well as athletes in other sports. Many studies have been conducted to evaluate the effectiveness of these prevention programs. These training programs can be categorized as balance training, plyometric training, long-duration neuromuscular training, or short-duration warm-up programs.

Caraffa et al.[63] investigated the effects of balance training on ACL injury rates in male soccer players. The prevention program included 20-min five phase progressive balance training with different balance boards. The training was performed every day during pre-season and three times a week during the season for a total of three seasons. A total of 10 ACL injuries occurred to the 300 players in the intervention group, while a total of 70 ACL injuries occurred to the 300 players in the control group. The difference in ACL injury incidence between groups was statistically significant. However how the participants were assigned to the intervention or control group and how the proprioceptive training reduced ACL injury incidence were not clear. Söderman et al.[64] studied the effects of balance board training on ACL injury rates in female soccer players. A total of 121 players in seven teams were randomized assigned to a training group and 100 players in six teams to a control group. The participants were instructed to perform a 10−15 min balance training on a balance board every day for 30 days and then three times a week for the rest of the season. With a 37% drop-out rate, four ACL injuries occurred among 62 players in the intervention group, while one ACL injury occurred among 78 players in the control group during the season. Balance board training could not prevent ACL injury for female soccer players at the given level, which is contradictory to the previous study.[63]

Pfeiffer et al.[65] studied the effects of a plyometric training program on ACL injuries in high-school female soccer, basketball, and volleyball players. A total of 577 players were included in the training group and 862 players were included in the control group based on their willingness to participate in the training program. The 20-min training program consisted of exercises of jump landing techniques with a focus on a proper alignment of the hip, knee, and ankle. The training was performed twice a week throughout the 9-week season. The difference in the incidence of non-contact ACL injury between training and control groups after training was not statistically different. Heidt et al.[66] studied the effects of preseason conditioning on ACL injury rate in high school female soccer players. A total of 300 players were recruited while 42 of them were randomly selected to a conditioning group and rest as control group. The conditioning included two treadmill sessions and one plyometric session per week over a 7-week period with an aim to improve cardiovascular conditioning, plyometric work, agility, strength, and flexibility. One year after the conditioning, one ACL injury occurred in the conditioning group, while eight ACL injuries occurred in the control group. The difference in injury rates between groups was not statistically significant. These two studies suggest that plyometric training alone is not likely to reduce ACL injuries.

Hewett et al.[67] investigated the effects of comprehensive neuromuscular training on non-contact ACL injury rates in high school soccer, volleyball, and basketball players. A total of 366 female athletes were included in the training group and 463 female athletes were included in the control group based on their willingness to participate in the program. An addition of 434 boys was included as another control group. The prevention program lasted 60−90 min and included multiple components (jumping/plyometric, flexibility, and strengthening). The training was performed 3 days a week for 6 weeks during preseason. After one season, no non-contact ACL injury occurred to the trained female athletes, while one non-contact ACL injury occurred to the untrained male athletes and five non-contact ACL injuries occurred to untrained female athletes. The investigators concluded that the training program significantly reduced the ACL injury rate. However, the results and conclusions of this study apparently depend on the statistical methods used for data analysis.[68,69] Besides, the need of significant extra time for this type of long-duration neuromuscular training might create obstacles in application.

Warm-up programs for ACL injury prevention have received great interests recently because of its short training duration and capability of being incorporated into regular training. Mandelbaum et al.[70] studied the effects of a warm-up program on ACL injury rates in female soccer players 14−18 years of age. Participants were assigned to a training or a control group based on their choices. The 20-min program included running, stretching, strengthening, plyometric, and agility exercises. The ACL injury incidence was 0.05/athlete/1,000 exposures in the intervention group compared to 0.47/athlete/1,000 exposures in the control group in the first year of the study. The incidence was 0.13 injuries/athlete/1,000 exposures in the intervention group compared to 0.51 injuries/athlete/1,000 exposures in the control group in the second year of the study. The differences in ACL injury incidences between the intervention and control groups were statistically significant in both years. The investigators concluded that the ACL injury incidence in the intervention group was significantly reduced. This study was cross sectional in nature without random group assignment. Also the ACL injury incidences of the intervention and control groups before the experiment were unknown. Considering these significant limitations, the results of this study only demonstrated a difference in ACL injury incidence between groups that could not be interpreted as a decrease in the incidence within group due to the intervention.

Gilchrist et al.[71] conducted a randomized controlled trial to study the effects of a previously mentioned warm-up program[70] on ACL injury rates in female collegiate soccer players. Thirty-eight teams were randomized to an intervention group and 37 teams were randomized to a control group. Twelve intervention teams and two control teams dropped out of the study. A total of 583 players in the intervention group and 852 players in the control group completed the study. After one season of intervention, the overall ACL injury rate was 0.20/1,000 exposures in the training group compared to 0.34/1,000 exposures in the control group without statistical significance. Non-contact ACL injury rate was 0.06/1,000 exposures in the training group compared to 0.19/1,000 exposures in control group without statistical significance. However, the training group had a significantly lower ACL injury rate during practice and significantly lower ACL injury rate for athletes with a history of ACL injury compared to the control group. The authors concluded that the warm-up program decreased ACL injury rate, especially for those with a history of ACL injury. A more than 30% drop-out rate in the intervention group was a limitation of this study.

Hägglund et al.[72] conducted a randomized controlled trial to investigate the effects of a 15-min neuromuscular warm-up program on ACL injury rate in adolescent female soccer players. The training group had 2,471 players and the control group had 2,085 players. The program included six exercises focused on knee alignment and core stability which was performed twice per week. After a competitive season, the training group demonstrated a significantly lower ACL injury rate compared to the control group.

Steffen et al.[73] conducted a cluster-randomized controlled study to investigate the effects of a 15-min warm-up program on ACL injury rates in female youth players under the age of 17 years. The intervention group included 1,073 players and the control group included 947 players. The intervention program included ten exercises designed to improve core stability, balance, dynamic stabilization, and eccentric hamstring strength. The training was performed for 15 consecutive sessions and then once a week for the rest of an 8-month season. No statistically significant difference was found in the overall injury rate and ACL injury rate between the intervention and control groups. A low compliance rate was indicated as only 14 out of 58 training teams completed more than 20 training sessions.

The effects of ACL injury prevention programs on ACL injury rates in soccer are inconsistent. Although several studies reported that prevention programs reduced ACL injury rate among soccer players, significant limitations in research design restricted the interpretations of their results. A common limitation in these studies was the cross-sectional research design without pre-intervention injury incidence measures. In this situation, the results of those studies only showed that the intervention groups had significantly lower injury rate compared to control groups, and cannot be interpreted as the decrease in injury rate in intervention groups due to training. Therefore the effects of those training programs on the injury rate are essentially unknown. Another significant limitation in current literature on ACL injury prevention programs was that the mechanism of injury prevention of those intervention programs was not clear. Although each intervention program had a focus of training, which risk factors the intervention program modified was largely unknown, or the connections of the risk factors with the ACL loading mechanisms and injury rates were unclear. This limitation is largely due to the lack of understanding of risk factors for ACL injury. Considering this limitation, the inconsistent results of studies on ACL injury prevention programs should not be a surprise. Future intervention studies are encouraged to evaluate pre-intervention injury incidence as well as to measure ACL injury risk factors prior and after training to overcome these limitations.

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The clinical ineffectiveness of current ACL injury prevention programs could be attributed to low compliance.[74] Review of current ACL injury prevention programs showed that training programs in ACL injury prevention programs typically need 15−90 min,[24,75] which may be an explanation of the low compliance to ACL injury prevention programs in clinical applications as well as in studies. Efforts have been made in several recent studies to design new ACL injury prevention programs with minimal additional training time to improve the compliance to prevention programs.[76−78] Future studies are needed to evaluate the training effects of these programs on ACL injury rates.

5. Conclusion

ACL injury is common in soccer, and has significant impact to the quality of life of injured individuals and significantly increased financial burden to society. Understanding ACL loading mechanisms and risk factors for the injury is critical for designing effective prevention programs. Recent studies provided convincing evidence that tibial anterior translation due to shear force at the proximal end of tibia is the primary ACL loading mechanism. Great posterior ground reaction forces on the lower extremity and small knee flexion angles are major contributors to the increased shear forces at the proximal end of the tibia and thus tibia anterior translation. No evidence has been found showing that knee valgus moment is a primary ACL loading mechanism. The observed knee valgus motion in ACL injury cases are likely a post-injury event. The results of studies on ACL loading mechanisms are largely ignored in studies on risk factors for ACL injury. Many identified risk factors have little connections to ACL loading mechanisms. The results of studies on ACL injury prevention programs for soccer players are inconsistent. Current ACL injury prevention programs for soccer players are clinically ineffective due to low compliance. Future studies are urgently needed to identify risk factors for ACL injury in soccer that is connected to ACL loading mechanisms and have cause-and-effect relationships with injury rate, and develop new prevention programs to improve compliance.

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