Abstract

In recent years, the number of women playing sports has increased significantly. The passage of Title IX in 1972 had a significant effect in encouraging female participation in sports. This increase in women’s sports participation also led to a rise in noncontact anterior cruciate ligament (ACL) injuries. As ACL injuries in young female athletes have become a public health issue, much research has been done on risk factors and prevention strategies.

In recent years, the number of women playing sports has increased significantly. In the USA in 1972 only 1 in 27 girls participated in high school sports, amounting to less than 300,000 nationwide. The passage of Title IX in 1972 had a significant effect in encouraging female participation in sports. By 2002, this proportion increased to 1 in 2.5 girls, totaling nearly 3 million girls playing high school sports nationwide.\(^1,2\) The same effect was also seen at the college level, with the proportion of female college athletes increasing from 2% to 43% in the same time frame. Furthermore, in the last 10 years, there has been a 210% increase in female soccer players in the USA.\(^3\)

This dramatic increase in women’s sports participation led to a concomitant rise in noncontact anterior cruciate ligament (ACL) injuries. Competitive team sports including soccer, basketball, and volleyball are known to require lower extremity dynamic stability for movements, such as cutting, decelerating, and jumping. The literature is clear that these specific movements are risk factors for noncontact ACL ruptures, and these sports have been identified as those with the highest incidence of injury.

As ACL injuries, specifically those in young female athletes have become a public health issue, much focus has been placed on this topic in recent years. Roughly $100 million per year is spent on research of prevention strategies, but unfortunately this pales in comparison to the cost this injury is placing on society.\(^4\)

The consequences of ACL injury include both temporary and permanent disability with resultant direct and indirect costs. The cost of the MRI imaging, reconstructive surgery, implants used during surgery, post-op bracing, and rehabilitation are a huge economic burden, in addition to the psychosocial impact of such an injury. The potential loss of entire seasons of sports participation, loss of scholarship funding, and lowered academic performance can be devastating. Despite the significant research in this field, it continues to lack consensus.

In recent years, this topic has come into the limelight, with articles in national newspapers publicizing the topic widely in the public domain. This public attention has also sparked a tremendous amount of literature trying to elucidate the risk factors and recently training regimens to help prevent these injuries.

Risk Factors

In order to design and implement sport-specific prevention strategies, the first step is to identify athletes at risk. Only after risk factors have been elucidated can training programs be designed and implemented in high-risk populations. It is known that women are at a 4 to 6 times greater risk for sustaining a non-contact ACL injury compared to a male athlete, and recent studies have shown that the reason for this discrepancy is likely multi-factorial.\(^1,5,6\)

Environmental Risk Factors

Environmental risk factors encompass all factors extrinsic to the athlete. These include the weather, type of footwear,
playing surface, and sport. Most of this literature is based on American football, Australian football, and handball.

Scranton and coworkers showed higher ACL injury rates in the National Football League in dry weather conditions. Dry weather increases the friction coefficient and torsional resistance from the shoe-surface interface. In the Australian football literature, a month of dry and warm weather before a match and low rainfall in the year before a match were significantly associated with a higher incidence of ACL injuries. Torg and associates examined the effect of temperature on the torsional resistance of cleats on AstroTurf® in dry weather. He found that as the temperature increased from 52° to 110° the shoe-surface friction interaction increased, and the more at risk the player was to injury. Based on these studies, the optimal weather to help decrease ACL injuries seems to be wet and cold.

Shoe-surface interaction is very important to prevent injury. Playing surfaces with high grass cover and high root density, such as artificial turf, are associated with a higher friction coefficient and also a greater ground reaction force. Higher friction is associated with increased performance from improved traction but also increased injuries. In a study comparing indoor and outdoor soccer, a 6 times greater incidence of all injuries was found when the sport was played indoors. Based on these studies, the optimal surface to prevent injury is outdoors on natural grass.

It is known that the shoe to surface friction coefficient has an association with injury incidence, so it would make sense that the footwear themselves would have an effect as well. To date, no study has been published specifically looking at this, and no current consensus exists on whether the number, length, or cleat design has any association with ACL injuries. The Torg study referenced above did note that the “edge” cleat pattern was associated with a higher risk of ACL tears, as they have a significantly higher torsional resistance. There is a clear lack of randomized studies on this topic, and more research is needed.

Anatomic Risk Factors
There have been many anatomic risk factors that have been associated with increased ACL injury. To a significant extent, a patient’s anatomy is difficult to modify; therefore, there is limited potential for intervention for these risk factors.

Body mass index (BMI) is perhaps the only modifiable anatomic risk factor. Some studies have shown an association between increased BMI and a more extended lower extremity position with decreased knee flexion on landing, which has been shown to be an independent risk factor for ACL injury. However, other literature has shown no association between BMI and ACL injury in female athletes.

In 1938, Palmer and colleagues were the first to suggest that a pathologic relationship between the ACL and intercondylar notch could contribute to ACL injury. He described a mechanism by which the ACL could tear as it stretched over the inner margin of the condyle. Investigators in multiple studies have since correlated femoral intercondylar notch stenosis with ACL injury.

In female adolescent athletes, a smaller notch size has been shown to be correlated with injury risk, as the ACL impinges within the notch during knee rotation. Chandrashekar and coworkers showed that ACLs in women were smaller in length, cross-sectional area, volume, and mass when compared with males. He also found lower fibril concentration and lower percent area occupied by collagen fibrils in females versus males. This likely means that women have lower tensile linear stiffness with less elongation at failure with lower energy absorption and load at failure compared with men. This study was in cadavers, which may or may not be generalizable to in vivo.

A recent MRI study showed a significant correlation between notch surface area and ACL cross-sectional area. A small patient will likely have a small ACL and a small notch. It may be the ratio that matters more than the actual size. Though controversy exists over whether a smaller notch size correlates with higher rates of ACL injury, the recent consensus is towards a likely relationship.

High Q angles may be associated with increased dynamic knee valgus, resulting in ACL injury. Shambaugh and associates showed that female basketball players with ACL injuries had a significantly higher Q angle than their non-injured counterparts. However, many other studies have shown the Q angle not to be predictive of knee valgus or ACL injury risk.

Loudon and coworkers wrote a highly referenced article in 1996 titled “The relationship between static posture and ACL injury in female athletes.” He evaluated 20 ACL-injured females and 20 age-matched controls. Regression analysis revealed knee recurvatum and excessive foot pronation to be statistically significant differences between the 2 groups, and more commonly found in the ACL-injured athletes.

Figure 1 shows the posture of an athlete “at risk”: anterior pelvic tilt tightens the hip flexors and lengthens and weakens the hamstrings. A flexion moment at the hip is counteracted with an extensor moment at the knee, leading to knee joint hyperextension and knee recurvatum. The hamstrings should counteract knee recurvatum and prevent anterior tibial translation, but the hamstrings in these athletes are typically weak.

Foot pronation and tibial internal rotation occur normally during the contact phase of the gait cycle. Prolonged pronation of the foot produces excessive internal tibial rotation, which stretches the ACL over the lateral femoral condyle, and may produce a similar pre-loading effect on the ACL.

Beckett and colleagues in 1992 showed a direct relationship between foot pronation and ACL tears. Woodford-Rogers and associates compared gymnasts, football, and basketball players with a history of an ACL injury to matched uninjured athletes and found greater foot pronation in the ACL injured group. Recently, however, there have been multiple studies showing no correlation. Orthotics are an easy and quick fix to help correct the malalignment and
Hormonal Risk Factors

Hormonal risk factors for ACL injuries are a current field of research. Liu and coworkers showed that ACL cells have both estrogen and progesterone receptor sites. These sex hormones have been reported to affect the tensile properties of ligaments; however, all studies so far have been in animal models. Sex hormones have also been shown to decrease motor coordination and have effects on strength, aerobic and anaerobic capacity, and high-intensity endurance in female athletes.

There has been much disparity in studies concerning the time of the menstrual cycle when the greatest number of injuries occur; however, consensus seems to now be in the pre-ovulatory phase, which is consistent with the timing of the estrogen surge. Zazulak and colleagues performed a systematic Pubmed review on the effects of the menstrual cycle on anterior knee laxity. He found nine articles total, six of which showed no effect, while three showed significant associations between them. Each of these three studies showed an increase in knee laxity in the immediate pre-ovulatory and ovulatory phases of the menstrual cycle.

This finding has prompted research into whether birth control pills could play a role in the prevention of non-contact ACL injuries. There have been a few studies to date looking at this. Wojtys and colleagues obtained a urine sample from 69 female athletes within 24 hours of an acute ACL injury and measured estrogen, progesterone, and luteinizing hormone levels. These hormones allowed for the determination of which phase of the menstrual cycle the athlete was in. In women not taking oral contraceptives, a significant association was found between ACL injuries and the phase of the menstrual cycle, with significantly more injuries occurring during the early ovulatory phase. This association, however, was not found among women who were taking oral contraceptives.

Extrinsic factors, such as stress, nutritional status, and exercise, also affect menstrual cycles and hormone levels. More research is needed to better establish the effects of sex hormones on structure, metabolism, and mechanical properties of tendons and ligaments. This is currently a significant research focus; however, no strong consensus has been reached, and ultimately more research is needed to further understand this.

Neuromuscular Risk Factors

The current area of research showing the most promise focuses on neuromuscular control in the prevention of certain movements that are associated with ACL injury. Neuromuscular control refers to the unconscious activation of the dynamic restraints surrounding a joint in response to sensory stimuli. Unconscious muscle activation is crucial during many actions in sports, including when an athlete quickly changes direction, during quick deceleration and acceleration actions, and during cutting and turning movements. Each of these motions is a known risk factor for non-contact ACL injuries. This may explain why some athletes are more susceptible to injury than others, and also why there may be a role for prevention programs.

Hewett studied high school female athletes performing the drop jump test and found that “high-risk” athletes responded to loading the lower extremity with increased motion in the coronal plane. By having smaller hip and knee flexion angles at initial foot contact with the ground, greater impact forces are created and more stress is seen throughout the lower extremities. “Low-risk” athletes demonstrated a sagittal plane load absorption strategy, which helped to dissipate forces and decrease overall injury rates.

Muscles crossing a joint provide stability to that joint. As muscles fatigue, it has been proposed that better conditioned athletes will have improved neuromuscular control later in
games compared with de-conditioned athletes. There has been no evidence showing an increase in non-contact ACL tears at the end of a game or nearing the end of a season. More studies looking at this possible relationship are needed.

**Prevention Programs**

Prevention programs have been created in an attempt to reduce non-contact ACL injury rates. These programs usually target high-risk groups, specifically young female athletes, and aim to improve dangerous motion patterns. There has been much written regarding the various training programs, and their effects on risk factor modification and risk reduction of non-contact ACL injuries. While some have shown no improvement with certain interventions, most have shown some benefit to these activities and programs.

It is currently believed that high school athletes are of the utmost importance for education and screening. However, some have suggested starting even earlier than high school to possibly be able to affect children before they start a sport, in an effort to alter their unconscious muscle activation and integrate proper biomechanics and neuromuscular control at an earlier age. Also, many studies use college or even professional sports as their subjects, which may not be generalizable to younger athletes.

The interventions could occur pre-season, in-season, post-season, or a combination of the three. Pfeiffer and coworkers performed a prospective, controlled, non-randomized study focusing on female soccer, basketball, and volleyball players. The athletes performed strengthening and plyometric exercises in a post-training exercise program. They found no reduction in non-contact ACL injuries. Perhaps a fatigued athlete may not have the ability to adopt new motor control, and may even reinforce a pathokinematic one. Or perhaps, 9 weeks was not long enough for the neuromuscular adaptations to occur.

Most training programs in the literature are 6 to 8 weeks in duration, despite the fact that no studies have investigated the optimal duration based on outcome. Gilchrist and associates found that their intervention was most successful in reducing injury rates in the last 6 weeks of the season, perhaps due to the fact that athletes had more exposure to the program by then and a greater opportunity for neuromuscular re-education to occur.

To date, there is no standardized intervention program established to prevent non-contact ACL injuries. Table 1 lists known risk factors that have been studied and published extensively on the left. On the right is a list of technique flaws that can lead to non-contact ACL injuries. There does not appear to be an isolated risk factor presenting in all cases. Instead, a combination of risk factors may better predict those athletes who are at increased risk of injury.

Multi-component programs show better results than single-component programs to reduce incidence and risk of non-contact ACL injuries. These programs include lower extremity plyometrics, dynamic balance and strength training, stretching, body awareness and decision making training, targeted core and trunk control, agility training, hamstring strengthening, and proprioception and neuromuscular training.

Plyometrics are exercises that involve jumping or doing activities in rapid succession to produce fast and powerful muscle contractions. By repeatedly producing rapid lengthening and contracting of muscles, they get stronger. By consciously practicing the technique of landing from a jump in a controlled environment, the body learns how to “land,” and muscle memory will kick in when an athlete cannot focus all of their attention on technique, such as during a game.

Chimera and colleagues evaluated the effects of plyometrics on muscle activation and performance of the lower extremities during jumping exercises. Twenty female athletes playing college soccer and field hockey were divided into two groups. A post-hoc analysis found a significant increase in hip adductor muscles, as well as increased hamstring to quad co-contraction in the group who underwent plyometric exercises. By increasing activation in the hip adductors and the hamstrings with 6 weeks of plyometrics, it is possible that this could then reduce knee valgus and potentially prevent non-contact ACL injuries.

Since the mechanism of injury is multi-factorial, it makes sense that a prevention program should include a variety of interventions. Mandelbaum and coworkers performed a 2-year prospective, controlled, non-randomized intervention study for female soccer players aged 14 to 18 in Santa Monica, California. Eight hundred forty-four female soccer players from 45 teams were enrolled in the study, with 1,913

| Table 1 Risk Factors and Technique Flaws that Can Lead to Non-contact ACL Injuries |
|----------------------------------------|----------------------------------|
| Risk Factors                           | Technique Flaws                  |
| Weak hamstrings                        | Cutting, pivoting in erect position |
| Muscle fatigue                         | Decreased knee flexion with landing |
| Decreased core strength                 | Increased knee valgus with landing |
| Decreased proprioception               | Foot flat landing                 |
| High dorsiflexion of ankle             |                                  |
| Low trunk, hip, knee flexion angles    |                                  |

female athletes from 112 teams serving as the age- and skill-matched controls. The intervention included education, stretching, strengthening, plyometrics, soccer-specific agility drills, all designed to replace the traditional warm-up.2

The control group just performed their traditional warm-up exercises. They only used traditional soccer equipment, such as cones and soccer balls, to keep the program practical and cost effective. This was performed over a 2-year period, encompassing two seasons. They found an 88% decrease in non-contact ACL injuries in the intervention group during the first year, and a 74% decrease during the second season, compared to the control group. A weakness of the study was voluntary enrollment of teams into the intervention group; however, they did have a high compliance rate.

Gilchrist and associates recently performed a prospective, randomized, controlled intervention in Atlanta, Georgia, with 61 teams, totaling 1,435 female soccer players (852 in the control group and 583 in the intervention group). She utilized the same program as Mandelbaum used in California and added exercises complemented with educational videos. There was a 41% decrease in non-contact ACL injuries in the intervention group. Even more impressive were the 100% reduction of in-practice contact and non-contact ACL injuries and the 100% reduction of contact and non-contact ACL injuries during the last 6 weeks of the season.29

These studies bring up two very important topics: the issue of compliance and the gear needed for the programs. If these prevention strategies are to be generalizable, the simple fact is that many teams will not have access to gyms and special equipment. Mandelbaum’s study utilized only traditional soccer equipment, such as cones and soccer balls. These on-the-field programs may be more realistic, cost-effective, and feasible.

The issue of compliance is paramount in these studies. Perhaps compliance is the limiting factor to overall success of the intervention programs. Many coaches do not consider it a high priority concern, and utilizing these preventive programs pre-season and throughout the regular season is a lot of time and work, especially when a positive outcome is no outcome—not having any ACL injuries. The coaches, trainers, and athletes all need to be involved and invested.

Conclusion
It is known that most ACL injuries are non-contact. The majority of these occur in adolescent female athletes, playing primarily soccer, basketball, and volleyball. A sudden change of direction or cutting maneuver combined with deceleration and landing from a jump in or near full extension are the most common playing situations precluding an ACL injury. The combination of strong quadriceps and weak hamstrings predisposes an athlete to anterior tibial translation and stresses the ACL.

Specific risk factors have been defined that predispose an athlete to injury and make them high-risk. There is some evidence of environmental and other external risk factors that make an athlete susceptible to injury, and there is good data on mechanisms of injury, including biomechanical and neuromuscular behavior that puts an athlete at risk.

More research needs to be done to further understand the risk factors, specifically more biomechanical studies related to specific actions within each sport and then addressing these specifically in the prevention programs. Also the exact role of weather conditions, playing surface, shoe selection, shoe-surface interaction, and knee braces is warranted.

There is no standardized intervention program for the prevention of non-contact ACL injuries; however, research has shown multi-component neuromuscular training programs are more effective in decreasing the rates of these injuries. The primary goal of these programs is to teach athletes how to land and decelerate, with reduced coronal plane motion and increased hip and knee flexion. Pre-season injury prevention combined with in-season maintenance programs may be advocated to prevent injury. Compliance is directly related to a cost-effective and feasible program, utilizing sport-specific equipment and on-the-field training.

Despite the fact that there are still a high number of unanswered questions, there is good evidence to suggest that neuromuscular training and prevention programs do reduce the risk of non-contact ACL injuries in female athletes; however, more research needs to be done.

Disclosure Statement
None of the authors have a financial or proprietary interest in the subject matter or materials discussed, including, but not limited to, employment, consultancies, stock ownership, honoraria, and paid expert testimony.

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