Anterior cruciate ligament prevention strategies: are they effective in young athletes – current concepts and review of literature

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Purpose of review
Participation in sports is on the rise, with young athletes training year round and specializing at earlier ages, predisposing them to sports-related injuries. Once thought to be rare, injuries of the anterior cruciate ligament (ACL) are being seen with a greater frequency in the paediatric population. Numerous preventive training programmes have been developed. The purpose of this review is to discuss risk factors and the effectiveness of preventive programmes in the young athlete.

Recent findings
Most ACL prevention programmes take a multifaceted approach, targeting dynamic neuromuscular and proprioceptive deficits. Focus often lies on noncontact mechanisms of injury, jump and landing techniques, and improving movement patterns during pivoting, cutting and change in direction. However, the effectiveness of these programmes in skeletally immature athletes needs to be evaluated.

Summary
Early specialization and increased demand for peak performance at a time of major physiological change, lack of physical fitness and neuromuscular deficits have contributed to an increase in ACL injuries in young athletes. Various preventive training programmes have been developed, but their effectiveness is debatable. We encourage young athletes to partake in preseason training programmes focused on strengthening, neuromuscular and proprioceptive training units under the appropriate supervision of qualified personnel.

Keywords
adolescent, athlete, children, knee

INTRODUCTION

Sports participation is on the rise, with approximately 35 million children aged 5–18 years participating in organized sports in the United States [1,2]. As participation is on the rise, frequency of sports-related injuries has risen as well. Early specialization has led to peak performance expectations at younger ages, predisposing young athletes to serious injuries. Intrasubstance injuries of the anterior cruciate ligament (ACL) in children were once thought to be rare but are being seen with a greater frequency [3–9]. Approximately 100 000–200 000 ACL injuries are estimated annually in the United States, with high school female athletes suffering ACL injuries at a rate of one in 60–100 athletes [10▪,11]. ACL injury often presents with a potential loss of sport participation, possible loss of scholarships and possible decreased performance in the academic arena [12,13]. Nonoperative management in this age group is poor, with radiological evidence of increased rate of meniscal tears and degenerative changes [14,15]. However, controversy exists regarding operative technique and risk of growth disturbances [16]. In addition, more than 50% of patients show early signs of irreversible osteoarthritis within 10 years of ACL reconstruction (ACLR) [17]. Sports injuries early in life may also

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KEY POINTS

- Changes in neuromuscular control occur during puberty, which leads to an increased risk of ACL injury if not assessed and not addressed.
- Age-appropriate neuromuscular training during warm-up can prevent ACL injury in children and adolescents involved in competitive sports.
- ACL prevention programmes require a multifaceted approach with essential components focusing on strengthening, plyometric and agility training, proprioception and balance training, and neuromuscular training with an emphasis on feedback to modify technique.
- We advocate strengthening and physical movement training routinely in youth sports with an emphasis on proper landing techniques and coordinated movement patterns supervised by qualified professionals.

threaten general health maintenance efforts and contribute to obesity [18].

Given the serious impact of ACL injury in the young athlete, considerable effort has been directed towards prevention programmes. Technique and age-appropriate motor skills are vital for success in sport and injury prevention. Essential components of prevention programmes include strengthening, plyometric and agility training, proprioception and balance training, and neuromuscular training with feedback to modify technique. Recently, injury prevention is an area of increasing interest to all physicians, trainers, coaches and physical therapists. The purpose of this article is to review current literature researching the prevention programmes that target and efficiently address risk factors predisposing athletes to noncontact ACL injury.

INJURY MECHANISM AND MODIFIABLE RISK FACTORS

Effective injury prevention programmes identify and address underlying mechanisms of injury. It has been well established that 70% of ACL injuries occur by noncontact mechanisms [19,20▪]. In a recent review, Shimokochi and Shultz [21] reported knee loading as the primary mechanism of injury, with the highest ACL loads incurred during a knee valgus load combined with knee internal rotation and quadriceps force application with insufficient hamstring contraction or near full knee extension. These force combinations commonly occur during deceleration, change of direction and jump landings [20▪]. Many risk factors have been described in the literature; however, neuromuscular deficits have demonstrated the most promise in terms of altering movement patterns and decreasing subsequent ACL injury rates [22–29].

Neuromuscular and biomechanical deficits at the trunk and lower extremities during sports-specific tasks have been reported as the primary underlying risk factor for ACL injury [30]. Consensus exists in the literature that measurable neuromuscular imbalances of quadriceps, ligament, leg and trunk dominance leave athletes vulnerable to injury [31–33,34▪▪]. Ligament dominance demonstrates the tendency to allow ligamentous stress prior to muscular activation to absorb ground reaction forces (GRFs). Lack of dynamic muscular control leads to increased valgus motion and high torque at the knee and ACL (see Fig. 1a,b). Quadriceps dominance results from preferential activation of knee extensors over knee flexors during sports manoeuvres [17]. Ebben *et al.* [35] reported that women sustain quadriceps activation longer during cutting and that their hamstring-to-quadriceps activation ratios are lower. Leg dominance pertains to muscular strength and coordination imbalances of opposite limbs, which may place both limbs at risk. The weaker limb is compromised in its ability to dissipate forces. The stronger limb is subjected to high forces secondary to increased dependence and loading on that side (see Fig. 2a,b). Trunk dominance is caused by increased motion of the body's centre of mass due to the absence of neuromuscular control of the body mass during single-leg landing, pivoting or deceleration [17] (see Fig. 3a,b). The excessive trunk motion in the frontal plane and high GRFs and knee joint abduction load leave the joint vulnerable to injury [34▪▪].

Proprioception is important for neuromuscular control of the lower extremity, especially during perturbations, landing and cutting tasks [36]. It has been demonstrated that increased trunk displacement after sudden perturbations is highly sensitive for prediction of ACL injury [36,37].

Sex-specific differences are elicited at the onset of puberty and maturation and have been reported to contribute to sex disparity in injury rates [34▪▪,38,39]. Studies indicate [35,39–41] neuromuscular and biomechanical differences between sexes during maturation, leaving adolescent female athletes at a higher risk for injury if preventive measures are not taken. During rapid growth spurts, core strength, neuromuscular ability and proprioception may be imbalanced and contribute to an increased risk of ACL tears [30,40,42]. Moreover, delays or regressions in some neuromuscular mechanisms and coordination patterns may occur [40]. Therefore, care should be taken during this stage of growth to ensure that the demands placed on the

FIGURE 1. Ligament dominance: differences in valgus knee motion between women during a single leg squat. (a) Increased valgus motion in an untrained female athlete. (b) Proper knee alignment in a trained female athlete.

child's body do not exceed their physiological capabilities.

The literature is limited in relation to causes behind the increased rate of ACL tears in the prepubescent athlete [34▪▪,41]. Prior to puberty, no sex-related differences in ACL risk factors were observed [34▪▪,43,44]. Undeveloped physical skills, physical maturity and size, and lack of physical fitness during preadolescence have been correlated with injury predisposition [42,45].

ANTERIOR CRUCIATE LIGAMENT PREVENTION STRATEGIES

Competitive young athletes in landing and cutting sports such as soccer, football, basketball and volleyball are at an increased risk for ACL injury. Most ACL prevention programmes targeted towards competitive athletes include neuromuscular training, proprioception training and plyometric training. Neuromuscular training programmes are designed to enhance joint stability, improve joint position sense and develop protective joint reflexes to prevent injury [46]. Proprioception training is designed to improve coordination and balance in multiple planes of motion with perturbations. Plyometric exercises involve various jumping, landing and cutting manoeuvres in different planes of motion at varying intensity levels. Other common components include technique-movement awareness, strength and flexibility training [46]. During the last decade, numerous studies [17,20▪,22–27,29,33,34▪▪,46–49] have highlighted the importance and effectiveness of prevention programmes in this high-risk population of young athletes.

Studies have demonstrated the importance of a multifaceted approach to neuromuscular training that includes sports-specific plyometrics, agility training and strengthening to successfully reduce incidence of ACL injury [22–26,33,47]. Moreover, programmes that incorporate training as part of their warm-up and emphasize proper technique have been shown to be effective [17,20▪,33,34▪▪, 46,47].

Multifaceted neuromuscular training programmes

Gilchrist *et al.* [47] conducted a level 1 randomized controlled study in 2008 including 1435 athletes of

FIGURE 2. Leg dominance. (a) Weight shifted to nonoperative limb demonstrating increased dependence and loading on that side. (b) Weight is balanced evenly between both limbs after visual and verbal cueing.

61 National Collegiate Athletic Association (NCAA) Division I women's soccer teams into an intervention and a control group. The intervention group followed the Prevent Injury Enhance Performance (PEP) training programme, installed by the International Federation of Association Football (FIFA). The warm-up was performed before training for 20 min three times a week for 12 weeks and demonstrated a 70% decrease in noncontact ACL injury. In 2000, 1041 female soccer players from 52 teams received sports-specific training in a nonrandomized trial by Mandelbaum *et al.* [22]. The intervention group was compared with 1905 players from the same league who did regular warm-up exercises. The intervention group underwent a specific training consisting of education, stretching, strengthening, plyometrics and sports-specific agility drills. They observed an 88% decrease in ACL injuries during the first season and a 74% decrease during the second season in the intervention group. In 2000, Heidt *et al.* [23] included 42 female soccer players into their Frappier Acceleration Training Program and compared them with 258 controls. A 7-week training programme, including cardiovascular conditioning, strengthening, and flexibility and plyometric exercises, was established in the intervention group. They observed nine ACL injuries over the period of 1 year, of which eight occurred in the control group. Myklebust *et al.* [27] conducted a prospective intervention study of female Norwegian handball athletes from divisions I, II and III. They found a significant reduction of ACL injury rates in the elite division in those who completed the neuromuscular training programme compared with the control group [27]. Hewett *et al.* [24] published a prospective study in 1999, through the Cincinnati Children's Hospital, which evaluated the effect of neuromuscular training on the incidence of knee injury in female athletes throughout their high school soccer, volleyball and basketball seasons. Group 1 consisted of 366 high school girls who underwent a neuromuscular training programme that was designed to improve flexibility and muscular strength. Group 2 consisted of 463 girls, who did not participate in the 6-week training programme but were involved in competitive sports. Group 3 acted as a control group and consisted of 434 untrained men. They reported a statistically significant reduction of ACL injuries in group 1 compared with group 2. A cohort study by Hewett *et al.* [33] incorporated a programme consisting of strength, power, agility, plyometric jump training with an emphasis on technique and maximum vertical-jump height in the intervention group (female volleyball, soccer and basketball players). The female control group had a 3.6 times higher incidence of knee injury than the female intervention group. In a study out of Oslo in 2005, Olsen

FIGURE 3. Trunk dominance. (a) Increased motion of the body's centre of mass in an untrained male athlete. (b) Balanced body's centre of mass in a trained male athlete.

et al. [25] found a positive effect of a structured warm-up programme in 120 team handball clubs. The players were aged 15–17 years and the warm-up was structured to improve running, cutting and landing techniques as well as neuromuscular control, balance and strength. This study demonstrated effectiveness in prevention of ankle and knee injuries; however, it was not specific to ACL injury. Petersen *et al.* [26] studied 276 German female handball players. One hundred and thirty-four players were included in a specific training programme, including balance board exercises and jump training. During one season, they observed six ACL injuries, of which only one occurred in the intervention group. They concluded that proprioceptive training significantly reduced the risk of ACL injury. This study demonstrated the importance of a multifaceted approach. Other studies that looked at proprioception alone were not as successful. Soderman *et al.* [50] reported that balance board training in female soccer players in Sweden did not result in any improvement in terms of traumatic injury of the knee. On the contrary, Caraffa *et al.* [51] conducted a prospective study including 600 soccer players in Italy and encountered a significant reduction of ACL injuries in the intervention group that underwent proprioceptive training using special wobble boards. This group, however, only included male soccer players, who demonstrated decreased risk in comparison with females.

All of the mentioned studies demonstrated the effectiveness of prevention strategies in high-risk athletes. However, there are no data on this point to support neuromuscular training programmes to be successful in children and adolescents who do not participate in organized sports. Studies that investigated the impact of warm-up, proprioceptive training and plyometric exercises separately from each other encountered contrary results, demonstrating the importance of a multifaceted approach.

Plyometric and agility training

Several studies have demonstrated the importance of monitoring technique training during plyometrics and sports-specific tasks to reduce injury risk.

Mizner *et al.* [52] demonstrated in 2008 that female athletes were able to make significant changes in landing mechanics after a brief verbal instruction. Pfeiffer *et al.* [53] observed 1439 high school athletes in Idaho involved in competitive soccer, basketball and volleyball in a prospective cohort design. Over the period of two consecutive seasons, 577 athletes in the intervention group participated in a plyometric-based exercise programme twice a week. There was no detectable difference, suggesting that a plyometric-only programme was not effective in reducing ACL injury risk. Imwalle *et al.* [54] found significant increases in internal rotation at the hip and knee during a 90° cutting manoeuvre versus 45°. This article demonstrated the importance of neuromuscular training at various angles and planes, as well as hip, hamstring and core strengthening. Agility training programmes that have incorporated unanticipated directional changes as well as cutting technique modifications via feedback have demonstrated improved medial hamstring activation during pivoting and a significant reduction in knee valgus loading during planned and unplanned conditions [55,56].

EFFECTIVENESS OF ANTERIOR CRUCIATE LIGAMENT PREVENTION PROGRAMMES

Most ACL prevention programmes include components of neuromuscular, proprioception and plyometric training and have been proven effective in producing biomechanical changes and reduction in ACL injury [57▪▪]. However, the practicality of some programmes for many individuals and teams may be limited secondary to needed equipment and time constraints. A neuromuscular training programme in a warm-up format minimizes time requirements and improves practicality and compliance. A review by Alentorn-Geli *et al.* [58] found that training targeted towards improving performance measures resulted in an improved compliance ranging from 80 to 90%. A drawback of the warm-up format is the lack of high-intensity overload and lack of measurable athletic performance enhancement effects [20▪,58].

Neuromuscular training programmes have a significant effect on the reduction of relative ACL injury risk in female athletes in high-risk landing and cutting sports because the neuromuscular deficits that put them at risk have been shown to be ameliorated with neuromuscular training [34▪▪]. Comprehensive warm-up programmes to improve strength, awareness and neuromuscular control during static and dynamic movements have been shown to reduce the risk of lower extremity injury [29]. Some neuromuscular training warm-ups that exist today are the PEP, the Knee Injury Prevention Program (KIPP), the Knee Ligament Injury Prevention Programme (KLIPP), the HarmoKnee programme and the '11+' programme [30,58,59].

The PEP programme includes basic warm-up exercises, stretching, strengthening exercises for the trunk and lower extremities, plyometrics and soccer-specific agility drills [17,20▪]. The KIPP consists of four progressive phases of jumping and landing forwards and backwards, two-footed and one-footed drills, and plyometric and agility training. The '11+' programme consists of three parts with a total of 15 exercises, which should be performed in a specified sequence at the start of each training session [59]. The key to the programme is proper technique. Part 1 includes running exercises at a slow speed combined with active stretching and controlled partner contacts. Part 2 consists of six sets of exercises focusing on core and leg strength, balance and plyometrics/agility exercises, each with three levels of increasing difficulty. Part 3 consists of running exercises at a moderate/high speed combined with planting/cutting movements. The HarmoKnee Programme consists of five parts, warm-up, muscle activation, balance, strength and core stability, which can be performed and integrated into regular soccer practice sessions. The KLIPP consists of a warm-up, stretching, strengthening, plyometrics, agilities and a cool-down exercise to address potential strength and coordination deficits.

In 2012, Herman *et al.* [59] published a systematic review that looked at the effectiveness of neuromuscular warm-ups. They reported the PEP programme was the most effective in reducing ACL injuries and was also shown to significantly reduce the risk of recurrence in those with previous noncontact ACL injuries [22,47,59]. In addition, the HarmoKnee and the 11+ programmes demonstrated a significant reduction of knee injury risk [29,60]. The KLIPP may reduce noncontact and overuse lower limb injuries; however, it has not conveyed any significant protection against knee injuries [59,61]. The successful warm-up strategies used by the 11+, PEP and KIPP were performed at every training/match session, suggesting that the effectiveness of neuromuscular warm-up strategies may depend on a dose–response relationship [59].

In summary, these studies suggest that a multifaceted warm-up approach may reduce the incidence of ACL injury in high-risk young athletes. Neuromuscular training has demonstrated approximately 50% reduction of ACL injury risk in female athletes [24,48,62]. In addition, protocols that integrate biomechanical, proprioceptive and strength training techniques have shown induction of an appreciable neuromuscular spurt and improved biomechanical techniques that lower risk [24,48, 62,63]. In contrast, those that target single-component training approaches have limited success [50,53].

These studies included adolescents and adults, and their conclusions may not apply to skeletally immature children who participate in organized sports. Nevertheless, we believe that age-appropriate exercises for skeletally immature children who are capable of learning a proper technique for landing and cutting may provide benefits that last a lifetime. However, the benefit of preventive exercises for children remains to be proven and requires further study.

CONCLUSION

Identification of at-risk athletes may be a first essential task before implementing specific training programmes. Consensus exists that sex differences emerge in neuromuscular control during puberty, which leads to differing rates of ACL injury between the sexes. This indicates that preadolescence seems to be a critical phase related to ACL injury risk factors [41,64–66,67■■].

Preliminary data reveal that integrative neuromuscular training protocols implemented in preadolescent and early adolescent stages may artificially induce the neuromuscular spurt [24,68] and have the potential to reduce the risk of sports-related injury in young athletes [24,49,68]. Therefore, injury prevention should be initiated in preadolescence to improve deficits that accelerate during maturation and lead to increased musculoskeletal risk [34■■]. Physicians and health-care providers have come together to make an effort to educate young athletes, trainers and parents about the effectiveness of prevention programmes.

In addition, youth should be encouraged to partake in strength and conditioning activities, and to provide neuromuscular balance. Strength training programmes have proven to be safe and effective for children as long as they are age-appropriate and supervised by qualified professionals [34■■,69,70,71■■]. The National Strength and Conditioning Association has produced a thorough position statement with specifics for age-appropriate guidelines [69]. Coaches, physicians, physical therapists and trainers should continue to advocate strengthening and physical movement training routinely in youth sports, with an emphasis on proper landing techniques and coordinated movement patterns. One of us (R.G.M.) recently published a book that describes a prevention programme that can be easily implemented by schools and sports teams as part of their warm-ups [67■■].

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Conflicts of interest

Dr Robert Marx receives royalties from Demos Health for the book The ACL Solution; Prevention and Recovery for Sport's Most Devastating Knee Injury.
There are no conflicts of interest.

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This is an excellent reference for parents, coaches and healthcare providers looking to incorporate preventive exercise into their young athlete's programme. The exercises provided are easy to implement into any programme, which allows improved compliance and injury reduction.