Current Concepts Review

Anterior Cruciate Ligament Injury-Prevention Programs

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A good anterior cruciate ligament injury-prevention program should:

- Incorporate feedback on technique
- Be performed throughout the year
- Focus on flexibility, strengthening, and plyometrics

Anterior cruciate ligament (ACL) injury continues to be one of the most debilitating injuries despite extensive research on ACL injury prevention and treatment over the past two decades. ACL injuries result in substantial physical and psychological morbidity to an athlete, with time lost from play, lost productivity, and an increased risk of the development of osteoarthritis. Female athletes have a fourfold to sixfold increased incidence of ACL injuries as compared with that of their male counterparts[1-3]. Since the implementation in 1972 of the Title IX Act, an equal opportunity act preventing sexual discrimination in activities at institutions that receive federal funding, female athletic participation has increased fivefold at the collegiate level and tenfold at the high school level, increasing the number of ACL injuries annually[1-4].

Approximately 70% of ACL tears occur from a noncontact injury and are theoretically preventable[5,6]. In this paper, we review the evidence-based mechanisms of injury, risk factors, screening programs, and prevention programs centered around noncontact ACL injuries, with particular emphasis on the female athlete.

Risk Factors

Most studies on risk factors focus on anatomical and biomechanical sex differences. There are modifiable and nonmodifiable risk factors. The modifiable risk factors are the premise of ACL prevention programs. Nonmodifiable risk factors will be minimally reviewed as they are out of the scope of this article.

Nonmodifiable Risk Factors

Nonmodifiable risk factors incorporate anatomical, developmental, and hormonal issues.

Notch Stenosis

One of the earliest theories regarding ACL injury was that a small notch impinges on the ACL[7]. Souryal and Freeman proposed the notch-width index (Figs. 1-A and 1-B) and found that notch-width stenosis was a significant ($p < 0.001$) risk factor for noncontact ACL injuries[8]. LaPrade and Burnett reported similar findings[9]. In a study of West Point cadets, Uhorchak et al. identified small femoral notch width and generalized laxity as significant risk factors ($p < 0.001$) of noncontact ACL injuries in both women and men[7].

Others have reasoned that a smaller notch-width index correlates to a smaller ACL[10]. Dienst et al. found a correlation between ACL size and notch-width index[10]. Chaudhari and colleagues found that ACL-injured patients had significantly smaller ACL volumes ($p < 0.0001$) as compared with those measured in controls[11].

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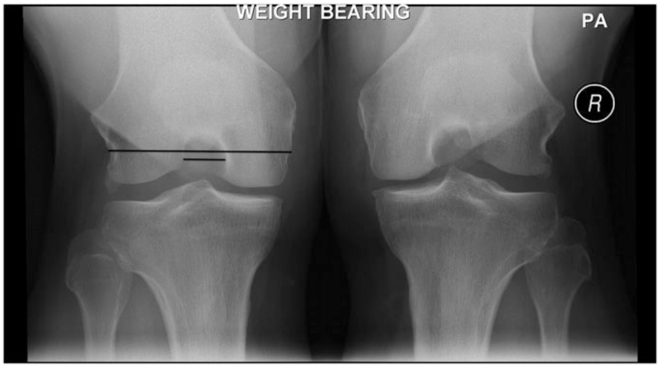

Fig. 1-A

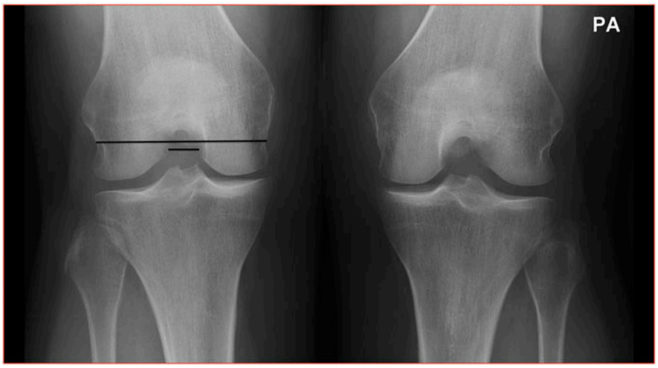

Fig. 1-B

The notch-width index (NWI) is determined by dividing the width of the intercondylar notch at the level of the popliteal groove by the bicondylar width at the same level, measured on a 45° flexion weight-bearing posteroanterior radiograph. A narrow NWI is defined as <0.2. **Fig. 1-A** represents a normal notch width (NWI = 0.23). **Fig. 1-B** represents a narrow notch width (NWI = 0.19). Both lines are generally measured at the same height (popliteal groove). They are offset here for illustrative purposes.

Ligamentous Laxity

Ligamentous laxity has long been considered a risk factor for noncontact ACL injuries. In a study of cadets by Uhorchak et al., generalized joint laxity was a significant risk factor for ACL injury[7]. Myer and colleagues identified knee hyperextension and laxity side-to-side differences as significant risk factors in female soccer and basketball players[12]. Ligamentous laxity has been demonstrated to be a risk factor for ACL injury in retrospective studies as well[6,13].

Tibial Plateau Anatomy

There has been a renewed interest in the anatomy of the tibial plateau and its contribution to ACL injury. Hashemi and colleagues found that both men and women with ACL injuries had significant increased lateral tibial slopes ($p = 0.02$ [males], 0.03 [females]) and shallow medial tibial depths ($p = 0.0003$ [males], 0.0004 [females])[14]. McLean et al. demonstrated posterior tibial slope (Fig. 2) to be significantly correlated with increased strain within the ACL as well as peak anterior tibial acceleration ($p = 0.007$)[15]. Lipps et al. demonstrated increased lateral tibial slope to be a significant risk factor of peak ACL strain ($p = 0.001$)[16]. Finally, in a retrospective case-control radiographic study, Todd and colleagues found a significantly increased posterior slope in the group with an ACL injury ($p = 0.003$)[17].

Hormonal Function

ACL fibroblasts have estrogen receptors[18,19], and estrogen affects the tensile properties of ligaments[19,20]. Hewett and colleagues performed a systematic review of seven studies that evaluated ACL injury and its association with the menstrual cycle[19]. The review showed a significant risk ($p < 0.0001$) of ACL injury in the preovulatory phase (i.e., the first half of the menstrual cycle), both when including and excluding the athletes who were taking oral contraceptive pills[19]. One of the seven studies found the opposite to be true, however[21].

Retrospective data have demonstrated lower injury rates, including ACL injury, in females taking oral contraceptive pills[19,22]. The proposed theory is that the oral contraceptive pills stabilize hormonal fluctuations throughout the cycle[19]. Martineau et al. found significantly increased anterior translation in female athletes who did not use oral contraceptive pills as compared with those who used oral contraceptive pills ($p = 0.008$)[23]. Hewett et al. also reported increased dynamic and passive stability in users of

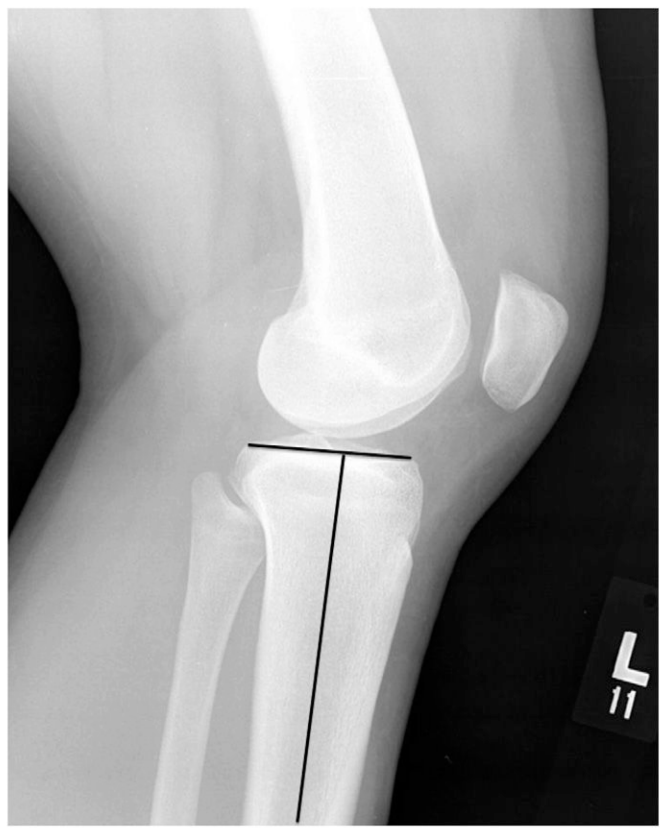

Fig. 2

To determine the posterior tibial slope, a line is drawn down the longitudinal axis of the tibia on a true lateral radiograph. Then a line is drawn from the peak anterior and posterior points on the medial tibial plateau. The posterior tibial slope is defined as the angle between the line joining the tibial plateau and the line perpendicular to the longitudinal axis.

oral contraceptive pills as compared with nonusers[19]. No conclusive evidence correlates hormonal fluctuations with ACL injury and the effects of oral contraceptive pills[19].

Neuromuscular Maturation

Studies regarding the incidence of ACL tears have found no difference between preadolescent males and females[24]. However, the difference becomes marked following maturation, concluding that only males undergo a so-called neuromuscular spurt—an increase in power, strength, and coordination that corresponds to maturational stage and allows increased neuromuscular control[24].

This neuromuscular spurt has been evaluated with longitudinal studies comparing boys and girls from puberty through maturation[25]. Martin et al. found that maximum short-term leg peak power was not gender divergent until the age of fourteen[25]. After age fourteen, peak power values are significantly higher in boys ($p < 0.05$)[25]. Hewett and colleagues discovered that, following the onset of maturation, female athletes landed with significantly more medial knee motion and greater maximum lower extremity valgus than male athletes did ($p < 0.01$)[24]. There were no differences preceding maturation[24].

When studying differences between pubertal and postpubertal years, Quatman et al. found that boys demonstrated increased vertical jump height and reduced their landing ground-reaction force, whereas girls did not[26]. These studies support a maturational neuromuscular difference between males and females.

Modifiable Risk Factors

Unlike anatomic risk factors, neuromuscular imbalances are modifiable[27]. Hewett et al. categorized neuromuscular imbalances into four groups: ligament dominance, quadriceps dominance, leg dominance, and trunk dominance[27].

Ligament Dominance

Hewett et al. defined the neuromuscular imbalance responsible for valgus collapse as ligament dominance[28]. With ligament dominance, the supporting muscular groups surrounding the knee do not adequately contract and absorb the ground reaction forces. Therefore, more force is imparted through the static restraints, including the bone, cartilage, and ligaments[27].

All lower-extremity muscles contribute to dynamic knee stability, but the posterior kinetic chain, comprised of the gluteal muscles, hamstrings, and gastrocnemius-soleus complex, is theoretically the most important in the prevention of ACL injury[27]. Improper recruitment of these muscles during landing tasks results in higher abduction moments, with increased load transmission to the ACL[29-34].

Multiple studies have demonstrated ligament dominance as a risk factor for ACL injury. Ford et al. studied high-school athletes performing a drop vertical jump with retroreflective markers and motion analysis. Females landed with a greater maximum valgus knee angle and greater total valgus knee motion than males did[35]. Females additionally produced greater side-to-side differences[35]. Hewett et al. performed a prospective, controlled cohort study following 205 female athletes over their respective seasons after assessing preseason neuromuscular control through three-dimensional kinematics with the use of retroreflective markers[36]. The nine ACL-injured athletes exhibited a 2.5 times greater knee-abduction moment, an 8° greater knee-abduction angle at landing, and a 20% greater ground-reaction force than the uninjured athletes did[36].

Quadriceps Dominance

When landing, females preferentially activate their quadriceps muscles more than males do. This results in a stiff-legged extended landing posture rather than a flexed, more ACL-protective position. This quadriceps-active landing technique has been termed *quadriceps dominance* by Hewett et al.[27]. The hamstring musculature theoretically acts as an agonist to the ACL, preventing anterior tibial translation, while the quadriceps acts as an antagonist, exerting a strain on the ACL, with maximum strain in the last 30° of extension[37].

In a cadaveric study, Withrow et al. established that increasing hamstring force during a simulated jump-landing decreased the peak relative strain in the anteromedial bundle of the ACL by 70%[34]. An erect landing position preferentially activates the quadriceps, exerting an anterior shear stress to the knee[27,34]. The protective posterior pull of the hamstrings is lost, placing the ACL at greater risk of rupture[27].

Huston and Wojtys demonstrated that female athletes generated maximum quadriceps force before, rather than after, maximum hamstring torque, when loading the ACL[38]. In another laboratory study, Chappell et al. evaluated recreational athletes via electromyography and kinematics through the use of retroreflective markers and video analysis[29]. Female subjects exhibited decreased knee flexion, decreased hip flexion, and increased quadriceps activation[29]. Hewett et al. demonstrated that a plyometric training program designed to decrease ACL injury resulted in significantly increased hamstring-to-quadriceps torque ($p < 0.05$) and a 22% decreased impact force ($p = 0.006$)[31]. Plyometric exercises refer to a power and agility program involving eccentric muscle contractions immediately followed by concentric muscle exercises such as jumping down and up from a box.

Myer et al. demonstrated that female soccer and basketball players who sustained ACL injuries had similar quadriceps strength and decreased hamstring strength than matched male controls did, whereas females who did not sustain injuries had decreased quadriceps strength and similar hamstring strength[39]. While evidence is inconclusive, it appears that landing with decreasing knee flexion angles and a decreased hamstring-to-quadriceps ratio places the athlete at risk for noncontact ACL injury.

Leg Dominance

Another important aspect of neuromuscular control involves side-to-side symmetry, balance, and control. In comparison with men, women depend more on one leg, which Hewett et al. termed *leg dominance*[27]. While the majority of athletes prefer using one leg for motions such as planting or kicking, the difference in muscular control is greater in female athletes[27,35,40,41]. Ford et al. found that female basketball players landed from a vertical jump with a significantly greater maximum valgus knee angle on their nondominant side as compared with their dominant side ($p < 0.001$), whereas males did not[35]. Hewett et al. consider an athlete to be leg dominant when the muscular asymmetry is measureable[27]. At this time there is limited evidence to support leg dominance as a definitive risk factor.

Trunk Dominance

The final neuromuscular risk is core dysfunction with an inability to precisely control the trunk in space, termed *trunk dominance* by Hewett et al.[27]. The premise is that athletes who do not possess core strength and trunk control lack dynamic stability, allowing greater movements outside a safe zone. This creates significantly larger moments about the lower extremity[27]. In a prospective cohort study, Zazulak et al. found that, compared with uninjured females, ACL-injured females displayed significantly greater maximum trunk displacement in all directions ($p = 0.005$)[42]. Lateral trunk displacement was the strongest predictor of ACL injury risk[42]. Trunk control seems to be a risk factor for ACL injury, although the data are currently inconclusive.

Environmental Factors

Environmental risk factors center on the shoe-surface interface. There is limited evidence to support increased friction between the shoe and surface as a predisposition to ACL injury. Lambson et al. prospectively evaluated 3119 high-school football players and found that a shoe design with longer cleats that were oriented for greater traction provided greater torsional resistance in laboratory testing and was associated with a significantly increased rate of ACL rupture ($p = 0.0062$)[43]. Olsen et al. retrospectively examined Norwegian team handball injuries and found a trend toward greater ACL injuries on synthetic, rubber floors[44]. Ekstrand et al. found no difference between natural grass and artificial turf in their prospective examination of injuries in male and female elite football players[45]. At this time, there is inconclusive evidence regarding shoe-surface interaction as an important risk factor for ACL injury[4].

Fatigue

Fatigue of stabilizing muscular groups may decrease dynamic stability, placing more strain on the ACL. Chappell et al. found significant increases in peak proximal tibial anterior shear forces ($p = 0.010$), increased valgus moments ($p = 0.03$), and decreased knee flexion angles ($p = 0.03$) in athletes who performed three stop-jump tasks after completing a fatigue exercise as compared with when they performed the tasks in a nonfatigued state[46]. While these data support fatigue as a risk factor, there is a paucity of research to validate this theory.

Prevention

Prevention programs focus on a number of key aspects of training: balance, proprioception, plyometrics, strengthening, endurance, and stability[47]. The variables of each program, including the exercise combinations, timing (preseason and/or postseason), and compliance may account for the variations in the outcomes of these programs (see Appendix). However, there is convincing evidence that correct neuromuscular training programs can decrease the rate of ACL injury in certain populations.

Prevention—Biomechanics

Hewett and colleagues first established a plyometric training program on the basis of neuromuscular differences observed in landing mechanisms between females and males[31]. They tested eleven high-school female volleyball players performing a jump block before and after a training program that focused on jump-training, emphasizing plyometrics, strengthening, and stretching. Following program completion, peak landing forces decreased 22%, knee abduction-adduction torques decreased 50%, and hamstring-to-quadriceps ratios improved 13% in the dominant leg and 26% in the nondominant leg[31]. Additionally, leg strength and vertical jump height increased significantly, providing an incentive for training[31].

Zebis and colleagues examined the effects of an ACL injury prevention program on hamstring activation during side-cutting maneuvers in elite soccer and handball players[48]. Following implementation of a training program, electromyographic activity of the medial hamstrings markedly increased during pre-landing and landing activity, while the quadriceps activity remained unchanged[48]. Nagano et al. also found significant ($p < 0.05$) activation of the hamstrings before foot contact during a single-limb drop landing after jump and balance training[49].

Myer et al. compared the effects of a plyometric training program to a dynamic stabilization and balance-training program in high-school volleyball players. Both groups reduced initial contact and maximum hip adduction angle during the vertical drop as well as decreased initial contact and maximum knee abduction angle during the medial drop landing[50]. The plyometric group increased initial-contact knee flexion and maximum knee flexion during the vertical drop jump, while the dynamic stabilization group increased maximum knee flexion during the medial drop landing[50]. The authors concluded that both aspects of training contribute to improved biomechanics. Plyometrics predominantly affects sagittal-plane mechanics during a vertical drop, and balance training affects kinematics during a single-legged drop landing[50].

Paterno and colleagues found significant improvements in single-limb total stability ($p = 0.004$) and anterior-posterior stability ($p = 0.001$), but not medial-lateral stability following Hewett's training program in high-school athletes[51].

The importance of feedback during training cannot be overstated. Laughlin and colleagues found that simple verbal cues and feedback, such as "land softly," resulted in a significant decrease in peak ACL force ($p = 0.05$), and a significant increase in hip flexion ($p = 0.003$) and knee flexion ($p = 0.007$) in a computer-simulation model[32]. Additionally, Oñate et al. compared the effects of an injury prevention program in patients with and without feedback. While all groups significantly improved knee angular displacement flexion angles ($p = 0.001$) and decreased peak vertical ground reaction forces ($p = 0.021$),

TABLE I Sportsmetrics Overview*

Phase	Duration	Purpose
Dynamic warm-up	5 min	Prepares body with functional-based activities, increases blood flow to the muscles, and improves flexibility, balance, and coordination
Plyometrics and jump training	30 min	The core of the program: focuses on correct jumping technique. Divided into 3 two-week sessions, develops muscle control and strength, and improves vertical jump height
High-intensity strength training	30 min	Emphasizes body alignment and form; focuses on core strengthening and muscular efficiency
Flexibility training	10 min	Achieve maximal muscle length; achieve muscular power throughout entire range of motion

*Website: http://sportsmetrics.org/

the feedback groups improved knee angular displacement flexion angles significantly (p = 0.04) more than the control[52].

Prevention—Clinical Studies

The first prospective, nonrandomized clinical study examining the protective effects of a neuromuscular training program was performed in 1999 by Hewett et al.[53], who followed 1263 soccer, volleyball, and basketball high-school athletes over the course of a one-year period. Groups were divided into a trained and untrained female group and an untrained male control group. The experimental group underwent a preseason neuromuscular training program, now known as the Sportsmetrics ACL prevention program (Dr. Frank Noyes, Cincinnati SportsMedicine, Cincinnati, Ohio) (Table I), that focused on flexibility, plyometrics, and weight training, and emphasized proper technique[53]. There were five noncontact ACL injuries in the untrained female group, one in the untrained male group, and none in the trained female group[53]. Overall, the untrained female group had a significantly increased (3.6 times; p = 0.03) incidence of injuries when compared with the trained female group[53]. There was no significant difference between the untrained male and trained female groups[53].

Mandelbaum et al. performed a prospective, nonrandomized cohort study to analyze the effects of their Prevent injury and Enhance Performance (PEP) ACL injury prevention program in female youth soccer players (age range, fourteen to eighteen years), over a two-year period[54]. The PEP program (Table II) is a twenty-minute program that is designed to replace the normal warm-up routine. It consists of education, stretching, strengthening, plyometrics, and soccer agility drills. A total of 1041 female athletes underwent the training during the first season, and 844 athletes underwent training during the second season. Age and skill-matched athletes in the same league served as the controls. The incidence rate, based on 1000 athletic exposures, was 0.05 in the trained group and 0.47 in the untrained group during the first year (p = 0.0001); 0.13 in the trained group versus 0.51 in the untrained group during the second year (p = 0.047); and 0.09 versus 0.49, respectively, overall (p < 0.0001)[54]. There was an 88% reduction in ACL injury during the first year, and a 74% reduction during the second year[54].

Gilchrist et al. examined the effects of the PEP program on the incidence of noncontact ACL injury in National Collegiate Athletic Association (NCAA) women's Division-I soccer teams in a randomized controlled trial. A total of 1435 athletes completed the study, 583 in the PEP group and 852 in the control. Overall, the rate of noncontact ACL injury was 3.3 times less in the PEP group than it was in the control group (p = 0.066)[55]. Athletes with a history of ACL injury in the PEP group were significantly less likely to suffer an additional injury[55].

Olsen et al. investigated the effects of a structured warm-up program, similar to the PEP program, in male and female youth (aged fifteen to seventeen) team handball over the course of a season[56]. The study included 120 teams that were randomized and matched. The intervention program focused on technique during cutting and jumping, and on balance and power training through wobble boards and plyometrics. There was an 80% reduction in all knee ligament injuries in the intervention group (fourteen versus three; p = 0.03)[56]. There was one ACL injury in the intervention group and five in the control group. Unfortunately, ACL injuries were not isolated for significance[56].

Pfeiffer et al. failed to find a benefit with an ACL prevention program in their two-year prospective study of high-school soccer, basketball, and volleyball athletes[57]. There were 577 athletes in the treatment group and 862 athletes in the control group. They used the Knee Ligament Injury Prevention (KLIP) program, which focuses on jump-landing and running-deceleration techniques, and decreased peak vertical impact force in a biomechanical study of college females[57]. They found a nonsignificant increased incidence (per 1000 exposures) in the intervention group (0.167) versus the control group (0.078), concluding that the program was ineffective[57].

Caraffa et al. developed the first study evaluating the effects of proprioceptive training on the incidence of ACL injury in 600 semiprofessional and amateur soccer players over a three-season period[58]. The groups were equally divided, with 300 players in the intervention group and 300 in the control group. The intervention group underwent a training program consisting of four different balance boards and five different phases of training. The incidence of ACL injury was 0.15 injuries per team, per season, in the intervention group and 1.15 injuries in the control group (p < 0.001), and the authors concluded that proprioceptive training can significantly reduce ACL injuries in soccer players[58]. No differentiation was made between contact and noncontact ACL injuries.

TABLE II PEP Program Overview*

Phase	Activity (Duration of Time To Complete Activity)	Time at Which Activity Occurs During Workout	Purpose
Warm–up (purpose: preparation)			
	Jog line-to-line (30 sec)	0 to 0.5 min	Prepare for training session
	Shuttle run (side-to-side) (30 sec)	0.5 to 1 min	Engage hip abductors and adductors; promote speed; avoid inward caving of knee joint
	Backward run (30 sec)	1 to 1.5 min	Engage hip extensors and hamstrings
Strengthening (purpose: leg strength)			
	Walking lunges (1 min)	1.5 to 2.5 min	Strengthen quadriceps
	Russian hamstring (1 min)	2.5 to 3.5 min	Strengthen hamstrings
	Single toe raises (1 min)	3.5 to 4.5 min	Strengthen calf; improve balance
Plyometrics (purpose: power, strength, speed)			
	Lateral hops over cone (30 sec)	4.5 to 5 min	Increase power and strength; emphasize neuromuscular control
	Forward and backward hops over cone (30 sec)	5 to 5.5 min	Increase power and strength; emphasize neuromuscular control
	Single leg hops over cone (30 sec)	5.5 to 6 min	Increase power and strength; emphasize neuromuscular control
	Vertical jumps with headers (30 sec)	6 to 6.5 min	Increase vertical jump
	Scissor jump (30 sec)	6.5 to 7 min	Increase vertical jump
Agilities			
	Forward run with 3-step deceleration	7 to 8 min	Increase dynamic stability of ankle-knee-hip complex
	Lateral diagonal runs	8 to 9 min	Encourage technique and stabilization of hip and knee; avoids ''knock-knee'' position
	Bounding run (44 yd)	9 to 10 min	Increase hip-flexion strength, power, and speed
Stretching (can be performed after warm-up)			
	Calf stretch (30 sec × 2 repetitions)	10 to 11 min	Stretch calf; focus on lengthening muscle
	Quadriceps stretch (30 sec × 2 repetitions)	11 to 12 min	Stretch quadriceps; focus on lengthening muscle
	Figure four hamstring stretch (30 sec × 2 repetitions)	12 to 13 min	Stretch hamstrings; focus on lengthening muscle
	Inner thigh stretch (20 sec × 3 repetitions)	13 to 14 min	Stretch adductors; focus on lengthening muscle
	Hip flexor stretch (30 sec × 2 repetitions)	14 to 15 min	Stretch hip flexors; focus on lengthening muscle

*PEP = Prevent injury and Enhance Performance. Website: http://smsmf.org/files/PEP_Program_04122011.pdf or http://pt.usc.edu/ACLprojectprevent/pep_tr.htm.

In a prospective, nonrandomized study, Myklebust et al. followed female team handball players over the course of three seasons[59]. There were 942 players in the control season, 855 players in the first intervention season, and 850 players in the second intervention season. The program consisted of a five-step balance training program focused on neuromuscular control and planting and landing skills. Although the results did not reach significance, the authors found a trend toward a reduction in the incidence of overall ACL injury ($p = 0.15$) and a more significant trend in the elite group ($p = 0.06$)[59].

Petersen et al. studied the effects of a prevention program on the incidence of injury in female German team handball players over the course of one season[60]. The training focused on balance and jump training. Importantly, the athletes were analyzed and given feedback regarding technique and landing positions. The study group encompassed 134 players with 142 controls. There were five ACL injuries in the control group (all noncontact), and one (contact) in the intervention group[60]. The authors did not separate contact and noncontact ACL injuries, making the incidence per 1000 exposure hours 0.21 in the control group and 0.04 in the intervention group[60]. The odds ratio was 0.17; however, the confidence interval (CI) was 0.02 to 1.5 as this was an underpowered study[60].

Smaller studies have been performed to examine prevention programs. Heidt et al. demonstrated a lower incidence of all injuries in the forty-two athletes in their intervention group ($p = 0.0085$)[61]. The incidence of ACL injury was lower as well (2.4 versus 3.1), but this was not significant as the study was underpowered[61]. Steffen et al. found no significant decrease in a cluster-randomized controlled trial examining female youth soccer and a set of exercises known as the "11."[62] While the design of the study was good, the compliance in the intervention group was only 24% (fourteen of fifty-eight teams)[62]. Finally, Söderman et al. also found no difference in the incidence of ACL injury in their underpowered prospective, randomized study evaluating female soccer players[63]. In addition to an extremely small number of athletes, their only intervention was balance-board training for a period of ten to fifteen minutes during the season[63].

Three meta-analyses have been performed to evaluate ACL injury prevention. In 2006, in a meta-analysis of six studies, Hewett et al. concluded that neuromuscular training programs have a significant effect on the prevention of ACL injuries[64]. In a 2010 meta-analysis, Yoo et al. found that the odds ratio of injury prevention was 0.40 with a prevention program (95% CI, 0.27 to 0.60)[47]. Subgroup analysis revealed that the following variables were significant: age younger than eighteen years, soccer rather than handball, combined preseason and in-season training rather than isolated preseason training, and plyometrics and strengthening exercises rather than balance training[47]. The authors concluded that the most effective program was a preseason and in-season neuromuscular training program with an emphasis on plyometric and strengthening exercises in the female athlete, especially in those who were younger than eighteen years[47]. In a 2012 meta-analysis, Sadoghi et al. found strong evidence for a significant, positive effect of ACL injury prevention programs ($p = 0.003$)[65]. The pooled risk ratio was 0.38 (95% CI, 0.20 to 0.72). Stratification by sex showed that female athletes had a risk ratio of 0.48 (95% CI, 0.26 to 0.89) or a risk reduction of 52%. Compared with females, male athletes had a risk ratio of 0.15 (95% CI, 0.08 to 0.28) or a risk reduction of 85%. There was no conclusive evidence supporting any one specific type of intervention program.

Screening

On the basis of the peer-reviewed prevention studies published in the English-language literature, Grindstaff et al. established that the number needed to treat in order to prevent one injury was eighty-nine over the course of one season[66]. This raises the issue of identifying the so-called at-risk group, rather than treating all athletes. By focusing on an at-risk group, prevention programs may be more effective.

To our knowledge, Myer et al. were the first authors to examine the possibility of screening female athletes and dividing them into high-risk and low-risk groups[67]. High-risk and low-risk groups were identified through motion analysis of a drop vertical jump and calculation of knee abduction moments. There was a significant ($p = 0.033$) decrease in knee abduction moments in the high-risk group and no significant difference in the low-risk group following implementation of a training program[67]. In similar studies, Myer et al. found that peak knee abduction angle, quadriceps-to-hamstring ratio, knee-flexion range of motion, body-mass index ratio, and tibial length were the most accurate at predicting knee abduction moments, with 77% to 85% sensitivity and 71% to 93% specificity[40,41,68].

DiStefano et al. performed a similar study evaluating the Landing Error Scoring System (LESS), a valid clinical movement-analysis tool[69]. They examined youth soccer players and found that those with the highest baseline scores improved the most with a neuromuscular program[69]. By using knee flexor and extensor preactivity electromyography on subjects who were performing side-cutting maneuvers, Zebis et al. identified patients at future risk of ACL injury[70]. With use of preseason electromyographic testing, they evaluated fifty-five elite female athletes with no history of ACL injury and followed them for two seasons. All five players who sustained a ruptured ACL demonstrated reduced electromyographic preactivity for the semitendinosus and elevated electromyographic preactivity for the vastus lateralis[70] ($p < 0.01$).

These studies confirm the ability to identify athletes who demonstrate at-risk kinematics; however, studies conclusively identifying at-risk athletes are lacking. Additionally, identification methods remain too labor-intensive for implementation on a large scale.

Compliance

Compliance is one of the main issues with implementation of a training program. This was especially evident in the study by Steffen et al., in which compliance was a dismal 24% (fourteen of fifty-eight teams)[62]. Coaches and players want to focus on improved performance rather than injury prevention.

However, performance can also be improved with these prevention programs. In the original study by Hewett et al., the athletes demonstrated improved lower-limb strength and vertical jump height[31]. Myer et al. examined the effects of a similar program on performance[71]. In addition to significant improvements in valgus torque of the knee, the trained group had a significant ($p < 0.001$) increase in maximum squat strength (i.e., a 92% increase in their maximum squat strength after finishing the program in comparison with their starting strength), single-leg hop distance, and double-leg distance and also had improvement in sprint times[71]. No improvements were seen in the untrained group[71]. These studies demonstrate that ACL prevention programs can increase performance, providing an incentive for coaches and athletic trainers to incorporate the program into the regimen of the team.

Recommendations and Conclusions

There is encouraging evidence supporting the possibility of preventing ACL injury, especially with the well-designed and scientifically validated programs. However, future research and nationwide collaboration are essential to generate ideal basic science solutions to this multifactorial injury. It is our recommendation that all female athletes undergo an ACL prevention program until more reliable methods of identification of at-risk athletes are developed. The training sessions should emphasize proper technique and should be performed year-round.

Appendix

eA A table showing an overview of studies is available with the online version of this article as a data supplement at jbjs.org. ■

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