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National Athletic Trainers' Association Position Statement: Prevention of Anterior Cruciate Ligament Injury

Darin A. Padua, PhD, ATC*; Lindsay J. DiStefano, PhD, ATC†; Timothy E. Hewett, PhD‡; William E. Garrett, PhD, MD§; Stephen W. Marshall, PhD*; Grace M. Golden, PhD, ATC, CSCS||; Sandra J. Shultz, PhD, ATC, FNATA, FACSM¶; Susan M. Sigward, PhD, PT, ATC#

*University of North Carolina at Chapel Hill; †University of Connecticut, Storrs; ‡Mayo Clinic, Rochester, MN; §Duke University, Durham, NC; ||University of Oregon, Eugene; ¶University of North Carolina at Greensboro; #University of Southern California, Los Angeles

Objective: To provide certified athletic trainers, physicians, and other health care and fitness professionals with recommendations based on current evidence regarding the prevention of noncontact and indirect-contact anterior cruciate ligament (ACL) injuries in athletes and physically active individuals.

Background: Preventing ACL injuries during sport and physical activity may dramatically decrease medical costs and long-term disability. Implementing ACL injury-prevention training programs may improve an individual's neuromuscular control and lower extremity biomechanics and thereby reduce the risk of injury. Recent evidence indicates that ACL injuries may be prevented through the use of multicomponent neuromuscular-training programs.

Recommendations: Multicomponent injury-prevention training programs are recommended for reducing noncontact and indirect-contact ACL injuries and strongly recommended for reducing noncontact and indirect-contact knee injuries during physical activity. These programs are advocated for improving balance, lower extremity biomechanics, muscle activation, functional performance, strength, and power, as well as decreasing landing impact forces. A multicomponent injury-prevention training program should, at minimum, provide feedback on movement technique in at least 3 of the following exercise categories: strength, plyometrics, agility, balance, and flexibility. Further guidance on training dosage, intensity, and implementation recommendations is offered in this statement.

Key Words: knee injuries, lower extremity biomechanics, neuromuscular control, injury prevention

Lower extremity injuries make up 66% of all sports injuries, the knee being the most commonly injured joint.[1] A particularly important and devastating type of knee injury is rupture of the anterior cruciate ligament (ACL). Unfortunately, surgical reconstruction and rehabilitation do not prevent long-term morbidity or decrease the risk of future ACL injury.[2–7] The costs associated with surgically reconstructed ACL injuries range from $5000 to $17 000 per patient; however, the estimated long-term societal costs may be as high as $38 000 per patient.[8–13] Perhaps even more alarming than the high financial costs was a report[14] indicating that the rate of ACL injuries is rising rapidly. Preventing ACL injuries during sport and physical activity may dramatically decrease medical costs and long-term disability.

Most ACL injuries do not involve a direct blow to the knee[15–17] but rather are noncontact or indirect contact in nature, involving uncontrolled lower extremity biomechanics. Thus, ACL injury prevention may be achieved by implementing training programs that improve an individual's neuromuscular control and lower extremity biomechanics.

Compared with single-component training programs, *multicomponent training programs*, or programs that require more than 1 type of exercise (eg, agility, balance, flexibility), appear more effective in reducing ACL injury rates.[18–21] However, no researchers have identified a single optimal preventive training program. As such, general guidelines and recommendations are provided for developing a multicomponent training program for preventing ACL injury. Based on available evidence, we recommend that a multicomponent injury-prevention training program include, at minimum, feedback on proper exercise technique for at least 3 of the following exercise types: strength, plyometrics, agility, balance, and flexibility. More detailed information on the rationale, development, and implementation of a multicomponent training program, as well as identification of target populations, is offered in the "Background and Literature Review" section.

Therefore, the purpose of this position statement is to provide certified athletic trainers (ATs), physicians, and other health care and fitness professionals with recommendations based on current evidence regarding the prevention of noncontact and indirect-contact ACL injuries in athletes and physically active individuals.

Recommendations are supported using the Strength of Recommendation Taxonomy (SORT) system.[22] The letter indicates the consistency and evidence-based strength of the recommendation (*A* has the strongest evidence base). For the practicing clinician, any recommendation with an A grade warrants attention and should be inherent to clinical practice. Less research supports recommendations with grade B or C; these should be discussed by the sports medicine staff. Grade B recommendations are based on inconsistent or limited controlled research outcomes. Grade C recommendations should be considered as expert guidance despite limited research support.

RECOMMENDATIONS

Effects of Injury-Prevention Training Programs on Injury Reduction and Performance Enhancement

Two primary areas of benefit are associated with injury-prevention training programs: decreased risk of ACL and other knee injuries and improved performance.

1. Multicomponent training programs that include feedback regarding technique and at least 3 of the exercise categories (ie, strength, plyometrics, agility, balance, and flexibility) are recommended to reduce noncontact and indirect-contact ACL injuries during physical activity.[18–21,23–31] *Strength of Recommendation (SOR): B*
    a. Females (aged 12 to 18 years) are strongly advised to perform a multicomponent training program to reduce the risk of noncontact and indirect-contact ACL injury during physical activity.[18,20] *SOR: A*
    b. Males are advised to perform a multicomponent training program to reduce the risk of noncontact and indirect-contact ACL injury during physical activity.[21,27] *SOR: B*
2. Multicomponent injury-prevention training programs are strongly endorsed for reducing noncontact and indirect-contact knee injuries other than ACL injuries during physical activity in females and males.[18,24,27,31–47] *SOR: A*
3. Multicomponent training programs are advocated to improve lower extremity biomechanics (eg, increasing sagittal-plane motion, decreasing frontal- and transverse-plane motion, and decreasing knee-joint loads)[48–62] and muscle activation (eg, increasing hamstrings and gluteal muscle activation)[51,63–65] and to decrease landing impact forces.[50,59,63,66–68] *SOR: C*
4. Multicomponent training programs are advised for improving balance.[44,59,69–71] *SOR: C*
5. Multicomponent training programs are endorsed for improving lower extremity strength and power.[48,49,51–53,61,63,72–75] *SOR: C*
6. Multicomponent training programs are promoted for improving measures of functional performance (eg, vertical-jump height, hop distance, hop speed, estimated $\dot{V}O_2max$, sprint speed).[48–52,61,63,69,73,76,77] *SOR: C*

Development of Multicomponent Injury-Prevention Training Programs (Exercise Selection, Intensity, and Volume)

The acute variables for injury-prevention training (ie, specific exercises to perform, order of exercises, repetitions, sets, intensity, tempo, rest periods between exercises, and training-session duration) vary among programs that successfully decrease injury rates and improve neuromuscular function and physical performance. Thus, we cannot recommend a specific multicomponent training program or group of exercises to prevent ACL injury. However, certain common features of the preventive training programs have been shown to be successful in reducing injury rates and improving neuromuscular function and physical performance. Therefore, general guidelines regarding the organization and types of exercises to include in multicomponent training programs are provided.

Exercise Selection and Training Intensity

7. A multicomponent preventive training program involves offering feedback on movement technique (eg, "land softly," "keep your knees over your toes," "bend your knees and hips") and should include at least 3 of the following exercise categories: strength, plyometrics, agility, balance, and flexibility.[18–20,23–27,29–31,78–84] *SOR: B*
8. Injury-prevention training exercises should be performed at progressive intensity levels that are challenging and allow for excellent movement quality and technique.[18,25,27,30,31] *SOR: C*

Training Volume (Frequency and Duration)

9. Multicomponent training programs should be performed during the preseason and in-season.[18,20,26,30,31] *SOR: B*
10. Multicomponent training programs should be performed at least 2 to 3 times per week throughout the preseason and in-season.[18,19,23,27,31] *SOR: B*
11. To maintain the benefits of reduced injury rates and improved neuromuscular function and performance over time, multicomponent training programs (preseason, in-season, and off-season) should be per-

formed each year and not discontinued after a single season.[85–87] *SOR: C*

Implementation of Multicomponent Injury-Prevention Training Programs (Program Adoption and Maintenance)

12. Multicomponent training programs should be regularly supervised by individuals who are skilled in identifying faulty movement patterns to ensure excellent movement quality and provide feedback on exercise technique.[18,19,23–25,31] *SOR: C*
13. Multicomponent training programs are effective when implemented as a dynamic warm-up or as part of a comprehensive strength and conditioning program.[18,19,23,31] *SOR: C*
14. To facilitate the adoption of and compliance with multicomponent training programs, we support the education of athletes, coaches, parents, and administrators on the following points related to preventive training programs.[88–95] *SOR: C*
    a. Lower extremity injuries are common in sports.
    b. Anterior cruciate ligament injury is a lower extremity injury that is particularly costly and potentially debilitating.
    c. Multicomponent training programs reduce ACL injury rates.
    d. Multicomponent training programs not only are effective in reducing injury but also can improve physical performance.
    e. Many elite-level athletes and coaches already incorporate injury-prevention training exercises as part of their in-season and off-season training programs.
    f. Multicomponent training programs can be seamlessly incorporated into preseason, in-season, and off-season training practices without taking time away from skill development.
    g. If time constraints are a concern, some evidence indicates that multicomponent training programs can be performed in 10 to 15 minutes as part of a dynamic warm-up before the start of practices and games.
    h. The rationale for exercise selection and the importance of maintaining proper technique and movement quality when performing exercises should be emphasized.
15. When implementing multicomponent training programs for children (ie, 15 years of age and younger), the following are advocated. *SOR: C*
    a. Incorporate movement patterns that are developmentally appropriate for children (eg, balancing, running, skipping, landing, squatting) in addition to sport-specific movements (eg, jump landings, jump stops, cutting maneuvers).[55,96,97]
    b. Focus on body control and movement quality by providing regular feedback about proper exercise technique.[55,96,98]
    c. Shorten the session or break it into multiple shorter segments depending upon the child's attention span.[55,72,96]

Targeting Individuals for Injury-Prevention Training Programs

All individuals involved in sports and physical activity are advised to participate in a multicomponent preventive training program. However, those who are active in particular sports or display certain traits should be targeted for preventive training as they either are at a relatively higher risk of ACL injury or have a greater potential for benefit.

16. Athletes participating in high-risk sports that involve landing, jumping, and cutting tasks (eg, basketball, soccer, team handball), especially females, should be targeted for injury-prevention training.[21,81,99,100] *SOR: A*
17. Because a history of ACL injury is one of the strongest predictors of future ACL injury, individuals with such a history, especially younger individuals who return to sport-related activities, should be targeted for injury-prevention training.[22,99,101–106] *SOR: A*
18. Children participating in higher-risk sports for ACL injury that involve landing, jumping, and cutting tasks (eg, basketball, football, soccer) should be targeted for injury-prevention training.[55,107–111] *SOR: C*

BACKGROUND AND LITERATURE REVIEW

Sport-related musculoskeletal injuries represent a serious long-term health concern for millions of Americans and need to be prevented when possible. Data suggest that sport-related injuries cause 20% of injured schoolchildren to miss at least 1 school day each year and 28% of injured working adults to lose at least 1 workday each year.[1,12] In addition to immediate time lost from work, school, or sport, musculoskeletal injuries are a primary reason people stop being physically active, which has detrimental effects on future health. Lower extremity injuries make up 66% of all sport-related injuries, and the knee is the most commonly injured joint.[1] A particularly important and devastating type of knee injury is rupture of the ACL.

Both females and males are at risk for ACL injury and may benefit from injury-prevention programs. Recent estimates from the general population indicate that 1 to 5 ACL injuries occur per 5000 persons over a lifetime.[15,112,113] In the United States alone, an estimated 200 000 ACL injuries occur annually[15]; however, the incidence of ACL injury is greater among athletic and military populations.[114] In Switzerland, the rate of ACL injury in the general population is less than 1 injury per 100 000 athlete-hours of sports exposure,[112] but the rate rises dramatically in specific athlete subgroups: for example, up to 1 injury per 1000 athlete-hours for females playing in professional soccer games.[115,116] Thus, the rate may be 10 to 100 times higher in elite athletes than in the general population. Males also sustain more ACL injuries than females in the general population.[15,108,113] Yet high school- and college-aged females participating in comparable sports (eg, basketball, soccer, softball) are at 1.5 to 4.6 times greater risk of experiencing an ACL injury compared with their male counterparts.[99,100,102,104,112] This is not to suggest that male athletes are at low risk for ACL injury. Among male high school football athletes, the rate of ACL injuries is 11.1 per 100 000 athlete-exposures, similar to that in female high school soccer and basketball athletes.[100] Perhaps most alarming are reports[14,117] indicating the rate of ACL injuries is rapidly rising.

Table 1. Overview of Level of Evidence and Effectiveness of Injury-Prevention Training Programs With Anterior Cruciate Ligament Injury as a Primary Outcome

Reference	Year	Strength of Recommendation Taxonomy Rating Sugimoto et al[123]	PEDro Score		Odds Ratio (95% Confidence Interval)[a]	Significance Level[a]
			Taylor et al[83]	Myer et al[121]		
Hewett et al[25]	1999	2	3	3	0.503 (0.097, 2.609)	.414
Heidt et al[24]	2000	1	4	5	0.762 (0.093, 6.255)	.800
Myklebust et al[31]	2003	2	3	5	0.870 (0.499, 1.516)	.624
Mandelbaum et al[19]	2005	2	3	3	0.179 (0.077, 0.413)	.001
Olsen et al[27]	2005	1	7	7	0.318 (0.086, 1.181)	.087
Petersen et al[29]	2005	2	3	2	1.497 (0.301, 7.440)	.622
Steffen et al[30]	2008	1	8	7	0.705 (0.189, 2.633)	.603
Gilchrist et al[23]	2008	1	4	4	0.563 (0.234, 1.357)	.201
Pasanen et al[28]	2009	1	Not reported	8	1.182 (0.329, 4.246)	.798
Kiani et al[26]	2010	2	4	4	0.085 (0.005, 1.535)	.095
LaBella et al[18]	2011	1	5	6	0.340 (0.068, 1.688)	.187
Walden et al[20]	2012	1	7	7	0.419 (0.169, 1.040)	.061
Soderman et al[44,b]	2000	2	4	4	5.310 (0.578, 48.779)	.140
Pfeiffer et al[43,b]	2006	2	3	2	1.497 (0.301, 7.440)	.622
Overall					0.541 (0.354, 0.828)	.005

Abbreviation: PEDro, Physiotherapy Evidence Database.

[a] Odds ratio, 95% confidence interval, and significance level data adapted from Myer et al.[121]

[b] Did not use a multicomponent injury-prevention training program.

Anterior cruciate ligament injury is a career-threatening, if not career-ending, injury in athletes. After ACL reconstructive surgery, an estimated 82% of individuals return to sport participation; however, only 63% return to their preinjury level of sport participation, and only 44% return to competitive sport.[118] The injury also carries other long-term consequences, as the odds of developing knee osteoarthritis are nearly 4 times greater after knee injury,[119] making a previous knee injury a strong risk factor for early knee osteoarthritis.[120] The rates of osteoarthritis after ACL injury range from 10% to 90% within 10 to 20 years.[3] Progression of knee osteoarthritis after ACL injury is not ameliorated by surgical reconstruction and rehabilitation: the risk of developing osteoarthritis is the same in ACL-injured patients who undergo surgical reconstruction as in those who do not.[2–7]

In addition to substantial long-term consequences and a high level of disability, ACL injury places a large burden on the health care system. A single ACL injury results in multiple physician and rehabilitation visits, generating significant costs to the health care system. A recent estimate[12] indicated that approximately $3 000 000 000 is spent annually on the ACL reconstruction process. Thus, given the associated frequency, disability, and costs, there is a great need to prevent ACL injuries.

Most ACL injuries are noncontact or indirect contact in nature and do not involve a direct blow to the knee.[15–17] Noncontact or indirect-contact ACL injuries involve uncontrolled lower extremity biomechanics, which suggests that some ACL injuries may be preventable. Therefore, the purpose of this position statement is to provide certified ATs, physicians, and other health care and fitness professionals with current best-practice recommendations regarding the prevention of noncontact and indirect-contact ACL injuries in athletes and physically active individuals. This position statement provides recommendations based on available current evidence related to the benefits, development, and implementation of injury-prevention training programs, as well as the identification of target populations for these programs. The majority of effective preventive training programs incorporate a multicomponent exercise program including feedback on proper exercise technique for at least 3 of the following types of exercises: strength, plyometrics, agility, balance, and flexibility.

Benefits of Injury-Prevention Training Programs

Reduced ACL Injury Rate. Multicomponent preventive training programs reduce the rate of ACL injury in males and females participating in sport.[18,19,23–31] In previous systematic reviews with meta-analyses,[83,121,122] the quality of the included studies has been evaluated (Table 1). These authors cited 7 level 1 studies[18,20,23,24,27,28,30] and 7 level 2 studies.[19,25,26,29,31,43,44] It should be noted that these reviews incorporated 2 studies that did not use a multicomponent training program[43,44] but instead either isolated plyometric[43] or balance[44] exercises, which did not reduce ACL injury rates. The effectiveness of injury-prevention training programs was also observed in the consistent findings of recent systematic reviews with meta-analyses. Overall, ACL injuries were reduced by 51% to 62% when athletes performed a preventive training program.[78,82] In addition, those who participated in a preventive training program had a greater relative risk reduction (RRR; 70%; 95% confidence interval [CI] = 54%, 80%)[79] and lower odds (odds ratio = 0.54; 95% CI = 0.35, 0.82)[121,122] of sustaining an ACL injury than those who did not. These findings are very promising regarding the ability to reduce ACL injuries by regularly performing an injury-prevention training program.

This body of evidence is limited by the small number of high-quality level 1 studies in which researchers specifically examined ACL injury after a preventive training program was implemented. However, the authors of 3 level 1 studies[18,20,23] reported a large reduction in ACL injury rates (64%–73%) when a multicomponent preventive training program was performed. Although Gilchrist et al[23] did not detect a statistically significant reduction in injury rate ($P = .06$), the 70% reduction they identified may be clinically meaningful given the difficulty of capturing a sufficient number of ACL injuries for adequate statistical power. However, these studies were limited to young (aged 13–24 years) females participating in basketball or soccer.

The findings of LaBella et al,[18] Walden et al,[20] and Gilchrist et al[23] support the use of multicomponent injury-prevention training programs to reduce ACL injury rates in young females (aged 13–24 years), who are at greatest risk for sustaining an ACL injury. These investigators studied training programs that were implemented by coaches or ATs who had undergone formal training, used a combination of progressive multicomponent exercises with an emphasis on technique, and were performed at least 2 to 3 times per week with good compliance. The other level 1 studies either lacked sufficient power for a statistical evaluation of the program's effects on ACL injury risk[24,27,42] or failed to detect statistical significance because of poor player compliance with the program.[30]

Limited research has examined the effects of preventive training programs on ACL injury rates in males. Silvers-Granelli et al[21] performed the only high-quality study that demonstrated a significant reduction (4.25-fold) in ACL injuries after collegiate male soccer athletes completed an injury-prevention training program. Other investigators[27,33,124] showed a reduction in ACL injuries, but their studies lacked the statistical power necessary to specifically examine ACL injury as an outcome. Future work is needed to further assess the effectiveness of preventive training programs in reducing ACL injuries in male athletes.

Reduced Lower Limb and Knee Injury Rate. A substantial body of evidence[18,21,24,27,31–47] supports the implementation of preventive training programs to reduce all noncontact and indirect-contact lower limb and knee injuries in both males and females. A meta-analysis[40] of multicomponent preventive training programs revealed that these programs significantly reduced lower limb injuries (RRR = 39%, 95% CI = 23%, 41%) and acute knee injuries (RRR = 54%, 95% CI = 24%, 72%). In a separate meta-analysis,[34] such training programs were effective in preventing all sports injuries. Based on this body of evidence, multicomponent preventive training programs should be performed regularly to reduce the risk of lower limb and knee injuries in males and females.

Improved Biomechanics, Neuromuscular Control, and Functional Performance. In addition to reducing the rate of ACL injuries, preventive training programs have other benefits related to improved biomechanics, neuromuscular control, and functional performance (eg, speed, agility, power, strength). These are important benefits to emphasize, as improvements in these measures may facilitate the long-term adoption of injury-prevention training programs by athletes and coaches. Lower extremity biomechanics, neuromuscular control, and functional performance measures are considered disease-oriented evidence according to the Strength of Recommendation Taxonomy.[22] Recommendations based on disease-oriented evidence are automatically classified as level C evidence. Thus, despite high-quality successful studies, only level C evidence exists for the benefits of injury-prevention training programs to improve lower extremity biomechanics, neuromuscular control, and functional performance. Furthermore, no evidence to date suggests that changing these disease-oriented measures will have a direct effect on patient-oriented outcomes (eg, injury rates).

Altered lower extremity biomechanics, such as limited sagittal-plane motion and excessive frontal- or transverse-plane motion, place abnormal loads on the lower extremity joints and soft tissues.[125,126] Consequently, these movements (eg, knee valgus, hip adduction, limited knee flexion) are frequently discussed as modifiable risk factors for ACL injury. Numerous authors[50,59,63,66–68] have reported success in reducing ground reaction forces with multicomponent preventive training programs and by increasing knee- and hip-flexion motion.[49–52] Although 1 or more of these changes in movement mechanics may provide mechanistic support for the success of preventive training programs, no data directly link these biomechanical changes to a reduction in ACL injuries. The literature is less conclusive regarding the ability to modify frontal- and transverse-plane motion at the knee and hip using preventive training programs. Some research supports the use of these programs to reduce excessive knee valgus,[59,127,128] knee rotation,[55] hip adduction,[59,62] and hip rotation,[49,62] but these outcomes have not been observed consistently. This discrepancy in the literature may be explained by large differences among studies in methods, target populations, and types of training programs.

Consistent evidence[44,59,69–71] indicated that preventive training programs can improve single-legged balance ability in active, asymptomatic individuals. Poor single-legged balance indicates impaired neuromuscular control and is a risk factor for lower extremity injury.[129–131] Recently, Steffen et al[132] demonstrated simultaneous injury-rate reductions and improved balance after adolescent female soccer athletes performed a preventive training program with high compliance. This finding supports the roles of balance and neuromuscular control in reducing the risk of and preventing injuries.

In addition to reducing injury rates and modifying neuromuscular factors related to injury risk, preventive training programs can also improve muscle strength[48,49,51–53,61,63,72–75] and athletic performance measures (eg, vertical-jump height, hop distance, hop speed, estimated $\dot{V}O_2$max, sprint speed).[48,49,52,61,69,73,76] Lower extremity strength and performance changes have been documented primarily after longer-duration (>60 minutes per session) training programs.[50,61,63,77] Some shorter-duration (approximately 15 minutes) training programs have demonstrated improved vertical-jump height in youth athletes, indicating that performance improvements may also be possible with briefer programs.[51,69] However, future investigation is necessary to elucidate changes in performance and muscle strength after preventive training programs because these changes may be critical elements to promote when pursuing adoption by coaches and athletes.

Preventive Training Program Components

No evidence suggests that a single optimal preventive training program exists. Instead, general guidelines should be considered when developing or implementing an injury-prevention training program. An overview of the types of exercises included in the ACL injury-prevention programs that have been studied to date is provided in Table 2. These

Table 2. Common Types of Exercises Included in Multicomponent Anterior Cruciate Ligament Injury-Prevention Training Programs

Reference	Year	Injury-Prevention Training Program Elements					
		Strength	Plyometrics	Agility	Balance	Flexibility	Feedback
Hewett et al[25]	1999	X	X	X		X	X
Heidt et al[24]	2000	X	X	X		X	X
Myklebust et al[31]	2003				X		X
Mandelbaum et al[19]	2005	X	X	X		X	
Olsen et al[27]	2005	X	X	X	X		X
Petersen et al[29]	2005				X		X
Steffen et al[30]	2008	X	X	X	X		X
Gilchrist et al[23]	2008	X	X	X	X	X	X
Pasanen et al[28]	2009	X	X	X	X		X
Kiani et al[26]	2010	X	X	X	X		
LaBella et al[18]	2011	X	X	X	X		X
Walden et al[20]	2012		X		X		X

guidelines can and should be modified for specific populations (eg, activity, age, sex, time available) to encourage program adoption, implementation, fidelity, and maintenance. Several meta-analyses[78–80,82–84,122] demonstrated the risk of an ACL injury was reduced between 39% and 73% in those who performed a multicomponent preventive training program compared with those who did not. The wide range of injury reduction is likely attributable to including athletes with contact or noncontact injury mechanisms. Furthermore, a recent meta-analysis[133] showed that a multicomponent program involving strength, balance, plyometric, and proximal neuromuscular control exercises was more effective in reducing ACL injuries than a single-component program. Based on these collective findings, a multicomponent preventive training program is recommended to reduce ACL and knee injury risk.

Although multicomponent injury-prevention training programs reduced ACL injury rates, few researchers have examined the ideal combination of program components (eg, exercise selection, volume, intensity). No randomized controlled trials have directly compared the effects of different training programs or the individual components of these programs on ACL injury rates. Thus, it is difficult to determine the combination of components that is most effective in a multicomponent training program.

Multicomponent preventive training programs typically include instruction and feedback on proper exercise technique for at least 3 of the following exercise types: strength, plyometrics, agility, balance, and flexibility.[83] Exercises used in multicomponent programs for reduction of ACL injury rates are described in Table 3. Strength-training exercises focus on improving muscle force production using body weight, free weights, or resistance machines. Plyometric training incorporates explosive movements, such as repeated jumping or bounding. Agility training addresses several important motor skills (eg, acceleration, deceleration, accurate changes of direction within the environment). Each component can be pursued individually, and then the components can be combined for agility training. Balance exercises often involve single-legged– or double-legged–stance tasks that incorporate various levels of visual input (eyes open → eyes closed), surface stability or hardness (stable → unstable and hard → unstable and soft), and external perturbations (no perturbation → moving extremities → catching a ball → partner perturbation). Lastly, flexibility training focuses on either static or dynamic stretching.

Successful multicomponent preventive training programs typically incorporate 1 to 3 exercises from each category (Table 3). These exercises are often performed in a 15- to 20-minute time period as part of a dynamic warm-up before sport activities. The specific exercises and intensity selected should be based on the individual's ability to complete the exercises with good technique.

The authors of meta-analyses[78,82–84,134] have attempted to address how the components of preventive training programs influence the ability to decrease ACL injury rates. Several investigators[83,84] have reported that plyometric and strengthening exercises were effective components for reducing ACL injuries, whereas balance exercises were not. However, Sugimoto et al[133] suggested that the failure to see a positive result from balance exercises may actually reflect the possibility that balance exercises are not protective in isolation but are protective in combination with other exercises. It is interesting that a greater reduction in ACL injury rates was observed in programs with more emphasis on and greater duration of static stretching.[83] However, only 3 studies included in this meta-analysis used static stretching, so caution is warranted when interpreting this finding. In addition, when the static stretching is performed during the course of a preventive training program should be considered. Static stretching can result in negative acute effects on maximal muscle strength and explosive muscle performance[135] and therefore may be best incorporated at the end of training rather than during a dynamic warm-up. In separate meta-analyses,[84,133] ACL injury risk was reduced in programs that incorporated strength, plyometric, and agility training. In 2 additional meta-analyses,[78,134] researchers were unable to evaluate the effects of isolated types of training because of heterogeneity among the articles included.

Based on the available evidence, we recommend that multicomponent injury-prevention training programs include feedback on movement technique and quality and incorporate exercises from at least 3 of the following categories: strength, plyometrics, agility, balance, and flexibility.[18–21,23–27,29–31,78–84]

An inverse dose response has been shown between preventive training programs and ACL injury rates (ie, increased dosage was associated with decreased ACL injury rates). The dosage may be influenced by both the volume and intensity of training. Volume is affected by the time in a single training session, the frequency of performing the program each week, and the total duration

Table 3. Specific Strength, Plyometric, Agility, Balance, and Flexibility Exercises That Have Been Incorporated Into Multicomponent Anterior Cruciate Ligament Injury–Prevention Training Programs[a]

Strength	Plyometrics	Agility	Balance	Flexibility
Abdominal curl-up[25,26,28]	Ankle bounce[18]	Forward-backward jogging[18,19,21,23,26,27,31]	Single-legged balance[21,27–31,44]	Calf stretch[19,23,24,26]
Prone plank[18,21,26,28,30]	Squat jump[18,19,21,23,25,27,29]	Side shuffle/gallop with arm swings[18,21,28]	Single-legged balance with upper body movement[21,27–31,44]	Quadriceps stretch[19,23,25,26]
Side plank[18,21,28,30]	Tuck jump[18,25]	High knee skipping[18,26,28]	Single-legged balance with partner perturbation[21,27–31]	Hamstrings stretch[19,23,25,26,28]
Back extension[25]	Scissor jump[18,19,23,25]	High knee carioca[18,27,28]	Single-legged balance on unstable surface[27–31,44]	Hip-adductor/groin stretch[19,23,26]
Hip bridge[20,26]	Stationary single-legged hop[20,31]	Parade[27]	Single-legged balance with lower body motion[27,28,30,44]	Hip-flexor stretch[19,23,25,26,28]
Leg press[25]	180° jump[18,25]	Forward running with stops[27]	Squat jump with stabilization[26]	Knee lifts[27]
Double-legged squat[18,20,21,27,28]	Broad jump[18,25,27–29]	Speed run[18,21,27]	Horizontal jump with stabilization[26]	Butt kickers[18,27]
Single-legged squat[20,21,26,28]	Lateral skate leap[21,28,31]	Shuttle run[18,19,23]	180° Jump with stabilization[30]	Arm swings[18]
Forward lunge[18–21,23,26,28]	Cycled split squat[28]	Diagonal run and cut[18,19,23,26]	Single-legged forward hop with stabilization[25,26]	Trunk rotations[18,27]
Prone lift[18]	Forward-backward line/cone jump and hop (double legged and single legged)[18–20,23,25,28-31]	Zigzag shuffle[30]	Single-legged sideways hop with stabilization[26]	Leg swings (front-back, side-side)[18]
Calf/heel raise[18,19,23,25]	Sideways line/cone jumps and hops (double legged and single legged)[18–20,23,28,30,31]	Diagonal skipping[18]		Iliotibial band/low back stretch[23,25,26,28]
Push-ups[18]	Single-legged hop for distance[18,25]	Plant and cut to athletic movement[21,27,31]		Hip in/out[21]
Pullover[25]	Combination jump-hop[18,25,28]	Bear crawl[18]		
Bench press[25]	Hop-hop stick landing[18,31]	Sideways shuffle with contact jump with partner[21]		
Lat pull-down[25]	Bounding[18,19,21,23,25,27,28,30]	Quick forward/backward run[21]		
Forearm curl[25]	Diagonal bounding[18]			
Nordic hamstrings lower/Russian hamstrings curl[19,21,23,26,27,28,30]	Bounding in place[18,25]			
Lateral lunge[18]	Side-to-side bounding[18]			
Diagonal lunge[18]	Box jump[21]			
	Mattress jump[25]			

[a] Strength, plyometrics, agility, and balance exercises are listed in order of increasing intensity or demand.

of the program over the entire training period. No original research studies have directly examined the effects of time in a single training session; however, decreased ACL injury rates occurred with preventive training programs that lasted approximately 15 minutes or longer (see Table 1 for ACL injury odds ratios between preventive-training and control groups).[18–20,23,27,31] In a recent meta-analysis,[123] training sessions of both short (<20 minutes') and long (>20 minutes') duration reduced the ACL injury risk, but long-duration training sessions lowered the risk of ACL injury by 26% more than short-duration sessions. Although long-duration training sessions may improve a program's effectiveness, this factor should be weighed against the potential negative influence on program adoption and compliance. Thus, preventive training sessions lasting at least 15 minutes appear to be effective in reducing ACL injuries.

Training-session frequency is also important, as a minimal number of sessions per week may be required to realize a program's injury-prevention benefits. Soligard et al[45] observed that players who performed a preventive training program an average of 1.5 times per week had a 35% lower risk of ACL injury compared with those players who were less compliant (<0.7 times per week). Steffen et al[132] also noted that individuals who performed a preventive training program an average of 2.2 times per week had a lower risk of lower extremity injury than low-compliance individuals (<1.5 times per week on average). In the 2 level 1 studies[18,20] demonstrating reduced ACL injury rates, the rate of compliance was high. On average, the intervention groups performed the preventive training programs 3.3 and 1.8 times per week in the LaBella et al[18] and Walden et al[20] studies, respectively. The authors of a recent meta-analysis[123] showed that 2 or more training sessions per week were associated with a 27% lower risk of ACL injury than a single session per week. Based on these collective findings, multicomponent preventive training programs should be performed 2 to 3 times per week to achieve the minimal dosage needed to reduce ACL injury rates.

Total program duration is also a consideration, as a minimal amount of total training time may be required to improve neuromuscular risk factors and lower one's risk of injury. Gagnier et al[78] reported that programs with a longer duration of follow-up (≥14 months) and a greater number of training hours per week (>0.75 h/wk) were more effective in reducing ACL injury rates. Yoo et al[84] demonstrated that performing preventive training programs during both preseason and in-season was more effective in reducing injury rates than performing them during either preseason or in-season alone. In contrast, Taylor et al[83] found that total training time and individual training-session duration did not affect ACL injury rates. Most recently, Sugimoto et al[123] investigated total training time per week (*low* = <15 minutes, *moderate* = 15–30 minutes, *high* = >30 minutes) and revealed that 68% of expected ACL injuries were avoided by performing a preventive training program multiple times per week and for more than 20 minutes per session. In another study,[87] a longer duration of training (9 months versus 3 months) led to better retention of improved landing biomechanics, but injury rates were not evaluated. To ensure sufficient time to modify one's neuromuscular risk factors and achieve long-term retention, we recommend that injury-prevention training programs be initiated early in the preseason and continue in-season to attain sufficient total training duration and reduce ACL injury rates.

In summary, although no specific injury-prevention training program, combination of exercises, single training-session duration, training-session frequency, or total training duration can be recommended, evidence suggests that multicomponent preventive training programs can reduce ACL injuries up to 75% if performed on a regular basis (2–3 times per week) beginning in the preseason. Future research is needed to investigate methods of optimizing preventive training programs in terms of exercise selection and training volume, duration, and intensity for specific groups of athletes.

Implementation of Preventive Training Programs (Adoption and Maintenance)

As previously described, regular compliance with a preventive training program is a critical factor in reducing ACL and knee injury rates. Even the best-designed preventive training programs will not be effective if they are not performed with a high compliance rate and good fidelity. Soccer players who were highly compliant with a preventive training program had an 88% reduction in the rate of ACL injury.[136] Sugimoto et al[123] observed similar findings in their meta-analysis, where the *compliance rate* was defined as the number of training sessions completed divided by the total number of sessions offered. Specifically, participants with low (<33.3%) and moderate (33.3%–66.6%) compliance rates demonstrated a 4.9 and 3.1 times greater relative risk of ACL injury, respectively, compared with participants whose compliance rates were high (>66.6%).

Given the importance of compliance to the program's success, it is vital to understand barriers to high compliance,[137] particularly when one considers that only 20% of youth soccer coaches reported performing a structured preventive training program.[138,139] Preventive training program design and implementation factors appear to influence compliance.[140] When designing a preventive training program, clinicians should give careful consideration to (1) the amount of time required to complete a single training session, (2) the use of sport-specific exercises, and (3) including a variety of exercises that may be modified or progressed over time.[137] Each factor has been reported[138,140,141] to affect regular performance of a preventive training program. Therefore, compliance may be negatively affected by programs that take longer than 15 minutes to complete, do not include sport-specific exercises, or lack variety or progression when performed over the course of a season.

Once the preventive training program is designed, consideration should be given to how it will be implemented.[137] We recommend implementation as a dynamic warm-up before training or as part of a comprehensive strength and conditioning program.[18–21,23–31,43,44] Failure to plan how the program will be implemented can result in poor compliance and lack of success. Key implementation factors to consider are (1) educating stakeholders on the relative benefits of performing a preventive training program, (2) training individuals to be confident in leading the training program and providing proper feedback, and (3) regularly monitoring for program compliance and correct exercise technique. It is important that administrators, coaches, athletes, and parents understand the importance and relative benefits of regular performance of a preventive training program. Thus, educating these individuals on how preventive training programs can reduce the injury risk and optimize performance may help to achieve "buy-in" and improve compliance.[138,140] All stakeholders must also be educated as to how the relative benefits of a preventive training program far outweigh any perceived barriers, such as a loss of practice time for skill development. Providing examples of how the program can be seamlessly integrated into existing practice and conditioning schedules and the potential additional benefit of enhancing sport-related performance may also be helpful in gaining support.

Proper training of the individual who will be leading the preventive training program is likely critical for achieving a high rate of compliance.[137] We recommend that a trained professional who can provide feedback on movement quality and exercise technique lead and directly supervise training sessions.[138,142] Recruiting trained professionals to lead and monitor a preventive training program has been shown to positively influence program compliance over the course of a season[85]; however, this may not be feasible in many situations. Often a coach or team captain is charged with leading a preventive training program. A lack of confidence on the part of the coach or player leading the training program can be a barrier to implementation. Thus, the individual leading a preventive training program should be trained on how to perform each exercise correctly and how to provide proper feedback on movement quality and exercise technique to ensure he or she is confident and competent in leading these exercises.[18,20,132] With consideration of these factors related to program design and implementation, in addition to appropriate exercise selection, the probability of achieving a high rate of compliance may be enhanced, thereby promoting more success in reducing ACL injury rates.

A final area of consideration for program implementation is the population to whom the program will be delivered. A recent meta-analysis[121] demonstrated a greater effect of preventive training programs when they were implemented during the midteens versus older ages, but no evidence indicated a specific age or maturation stage at which the program should begin. As such, we recommend all children who participate in sports involving landing, jumping, and cutting tasks (eg, basketball, soccer, football) that are high risk for ACL injury be targeted for preventive training programs.[55,107–111,121] It may be ideal to start preventive training programs in those younger than 15 years, given the greater effect of such training when implemented during the midteens versus older ages.[121]

Although early intervention in children may improve the long-term benefits of injury prevention, it is critical that preventive training programs be modified appropriately for younger athletes. Specifically, children may require special considerations in both program design and implementation to achieve optimal results. We recommend the following be considered when implementing preventive training programs for children: (1) Incorporate movement patterns that are developmentally appropriate for children (eg, balancing, running, skipping, landing, squatting) in addition to sport-specific movements (eg, jump landing, jump stop, cutting). (2) Emphasize body control and movement quality by providing regular feedback about proper exercise technique. (3) Use a multifaceted and integrated preventive training program. (4) Shorten the session or break it into multiple shorter segments depending on the child's attention span.[55,96]

Children need to develop a general foundation of motor skills and strength in order to decrease the risk of future injury[143] and optimize confidence when participating in physical activity. They develop fundamental motor skills, such as running, jumping, and landing, at different rates.[144,145] Implementing programs that match an individual child's cognitive and neuromuscular development levels will likely promote confidence and intrinsic motivation to participate and continuously improve.[97] It is also important to allow adjustments to the programs as necessary during development. This is especially true during adolescence, when rapid changes in limb length and body mass may result in muscle flexibility and strength imbalances, as well as temporary declines in coordination and balance.[143,146] Implementing integrated, phased programs that begin with basic fundamental exercises, such as a double-limb squat and stable balance exercises, may help ensure that all children acquire a basic foundation of strength, balance, and movement control. Children require continuous feedback about their exercise technique to optimize motor learning and appear to respond best to internal cues of attention, such as "bend your knees."[98,147] Programs should allow gradual, simple progressions (eg, advancing to single-legged exercises, unstable surfaces) and incorporate sport-specific exercises to promote the transfer of proper movement control to at-risk activities.[55] Shorter-duration programs per session (ie, 10 versus 20 minutes) may also help keep children's attention but consequently may require a higher volume of sessions for them to retain the improvements.[73,87]

Identification of Individuals for Preventive Training Programs

Preventive training programs are recommended for all athletes; however, they may be critical for individuals with a higher risk of injury. Sports involving frequent landing, cutting, or direction changes and decelerations, such as basketball, football, and soccer, have consistently been shown to carry a higher risk of injury than other sports.[100,104,148] Although males account for the highest absolute number of ACL injuries in the general population, females in high-risk sports (eg, basketball, soccer) have a 4 to 6 times greater risk of injury compared with their male counterparts.[15] High school football players have similar ACL injury rates to female basketball and soccer athletes, but these rates may include direct-contact injuries.[97] Consequently, we recommend these female athletes and male football players be specifically targeted to perform preventive training programs.

The individuals at highest risk for ACL injury are those with a history of an ACL injury, especially younger individuals who return to sport-related activities.[149–152] This elevated risk is consistent for both the ipsilateral and contralateral limbs, so preventive efforts should not focus solely on the previously injured limb. Preventive training programs can specifically reduce the elevated risk associated with repetitive ACL injuries. Gilchrist et al[23] demonstrated that after an ACL injury, individuals who performed a preventive training program reduced their risk substantially compared with athletes who did not perform such a program. Therefore, we recommend that athletes with a history of ACL injury perform preventive training programs to reduce the risk of reinjury.

Identifying individuals at high risk for ACL injury may allow clinicians to make prevention efforts more efficient in situations where resources, such as time and personnel, are limited. Proposed risk factors for ACL injury include but are not limited to faulty movement patterns, genetics, knee-joint laxity, and body mass index. Faulty movement patterns (ie, restricted knee or hip flexion or excessive knee valgus, hip adduction, or hip rotation) are considered modifiable risk factors for ACL injury.[153,154] Clinical movement screening tests have been shown to be reliable[155–157] and valid for assessing these high-risk movements[157] and injury risk[158] and should be considered in conjunction with preventive training programs. In addition to identifying high-risk individuals, these screening tests may help to improve adoption of and compliance with programs by demonstrating observable changes to coaches, athletes, parents, and other key personnel involved in athletic health decisions.

Implementing preventive training programs in athletes before high school may improve long-term compliance and outcomes. Earlier intervention may also be ideal because the middle-school age range is the best time for children to develop neuromuscular control. Additionally, motor development is not complete at this point and preadolescent children may be at an optimal age to master fundamental motor skills.[144] Improving neuromuscular control in children younger than 15 years may also decrease their susceptibility to injury during the highest-risk years (ie, adolescence). Furthermore, athletes who learn to perform preventive training programs as part of their sport activities at an early age may be more inclined to maintain this behavior as they develop because they perceive it as a normal part of sport. This attitude shift toward the implementation of preventive training programs is likely critical to ensuring widespread and lasting adoption of injury-prevention programs at all levels. In summary, we recommend that preventive training programs target not only individuals in high-risk sports, those displaying high-risk movement patterns, and those with a previous injury but also younger children (<15 years).

CONCLUSIONS

The majority of ACL injuries are noncontact or indirect contact in nature and involve uncontrolled biomechanics. Injury-prevention training programs that improve biomechanics and neuromuscular control can protect the knee joint from excessive loading and represent the best opportunity to reduce the risk of ACL and other traumatic knee injuries. Knowledge is growing about the ways to optimize preventive training programs in terms of exercise selection, training volume, and intensity; however, at this time, we can make only general recommendations related to the design or choice of an effective preventive training program. Multicomponent preventive training programs (including feedback on movement technique and quality in combination with exercises from at least 3 of the following categories: strength, plyometrics, agility, flexibility, and possibly balance) that are performed 2 to 3 times per week for approximately 15 to 20 minutes each session can substantially reduce ACL injury rates, up to 75% in females playing high-risk sports (eg, basketball, soccer). To reduce the risk of ACL injuries, especially in higher-risk populations, preventive training programs should be implemented as part of an athlete's preseason and in-season training. Implementing these programs at an early age (ie, before the age when injury rates rise) and continuing these efforts through an individual's competitive years may be particularly advantageous if we are to optimize motor-learning principles and ensure the retention of improved neuromuscular control to reduce the risk of injury.

Recommendations for future research are provided to improve the efficacy and effectiveness of future multicomponent preventive training programs in reducing ACL injury rates:

1. Although good evidence indicates that multicomponent preventive training programs are effective in reducing ACL injury rates in females, research in males is limited. Future investigators should examine the effectiveness of preventive training programs in males participating in high-risk sports for reducing ACL injury.
2. Recent meta-analyses of multicomponent preventive training programs suggest that including specific exercises (eg, strength, proximal control, or core stabilization) may be more effective in reducing ACL injuries, whereas other exercises may be less effective (eg, balance, static stretching). However, specific exercises for reducing ACL injuries have not been directly compared. Similarly, the role of exercise progression over the course of an injury-prevention program has not been examined. Future authors should assess the effects of exercise selection and progression to determine the most effective combination and progression of exercises for reducing ACL injuries.
3. A growing body of research is addressing the effects of exercise-based injury-prevention programs on biomechanics and neuromuscular control. However, these studies have not consistently investigated programs shown to be effective in reducing the risk of ACL or knee injuries. To guide the future development of effective and efficient multicomponent preventive training programs, we need continued research examining the underlying mechanisms (eg, biomechanics, neuromuscular control) of programs that have been successful in reducing injury risk.
4. The body of research evaluating prospective risk factors for ACL injury remains limited. Thus, it is not yet possible to identify those individuals who should be targeted for ACL injury-prevention interventions. High-quality, prospective cohort studies assessing factors such as biomechanics, neuromuscular control, genetics, body composition, knee laxity and geometry, and skeletal alignment are required to provide better insight into those who may benefit most from preventive training programs.
5. To have long-lasting public health benefits, an effective multicomponent injury-prevention training program must be adopted, implemented, and maintained by multiple parties (eg, coach, athlete, parent, administration). In addition, these programs must be performed with a high level of fidelity to maximize their benefits. Descriptions and recommendations for implementing multicomponent preventive training programs in real-world settings are limited, although recent research suggested that implementation planning can enhance adoption by athletes and coaches. Deficiencies in the ability to translate findings from controlled research studies to the real world greatly limit the public health effects of current programs. Future research into implementation of and dissemination strategies for multicomponent preventive training programs is needed to improve the adoption and implementation fidelity in real-world settings and maximize the population benefits of these programs.

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Address correspondence to Darin A. Padua, PhD, ATC, University of North Carolina at Chapel Hill, 204 Fetzer Hall, CB #8700, Chapel Hill, NC 27599-8700. Address e-mail to dpadua@email.unc.edu.