21 Effect of Intervention Programs on Reducing the Incidence of ACL Injuries, Improving Neuromuscular Deficiencies, and Enhancing Athletic Performance

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Abstract

This chapter reviews the current available data regarding the effectiveness of the ACL intervention programs in reducing injury rates, improving knee kinematic and kinetic factors, and enhancing athletic performance indicators. Three programs published to date that reported ACL injury rates in female athletes according to athlete exposures statistically reduced the injury rate. A multitude of studies have analyzed the effectiveness of knee injury prevention programs in changing kinematic or kinetic factors in female athletes. However, the effectiveness of these programs in altering neuromuscular indices under reactive, unplanned, actual athletic conditions remains largely unknown. While many studies have documented changes in athletic performance indicators following ACL injury prevention training in female athletes, the results remain mixed.

21.1 Introduction

Since the first publications of knee ligament injury prevention, training programs appeared in the sports medicine literature for skiing in 1995 [1] and female high school athletes in 1996 [2]; at least 30 intervention programs have been published that focused on female athletes (Table 21.1). Multiple investigations have been conducted to determine the effectiveness of these programs in reducing anterior cruciate ligament (ACL) injury rates [7, 18, 20, 25, 26, 31, 32, 34, 35, 39], improving knee kinematic and kinetic factors [2, 4, 5, 8–12, 15, 17, 19, 21, 22, 24, 29, 42–45, 48–57, 59, 61–63, 65, 67–75], enhancing strength or other athletic performance indicators [3, 5, 8, 10–15, 17, 19, 22–24, 29, 38, 42, 45, 48–51, 53, 54, 56–58, 61–63, 66, 67, 76, 77], and improving static and dynamic balance [13, 16, 29, 40, 47, 60, 64, 66].

There exist differences in opinion regarding the frequency, intensity, duration, and components that should comprise an ACL intervention training program. One issue is if a significant reduction in the injury rate can be accomplished with "warm-up programs" that are relatively short in session duration (10–20 min), but long in total training duration (for instance, one season). This is in contrast to preseason programs that last 6–8 weeks but require 60–90 min of training per session. A second issue is whether ACL intervention training should be modified according to the

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F. R. Noyes, S. Barber-Westin (eds.), *ACL Injuries in the Female Athlete*,
https://doi.org/10.1007/978-3-662-56558-2_21

Table 21.1 Summary of published ACL injury prevention programs for female athletes

Program or author (citation)	Program duration	Program components	ACL injury rate calculated by exposure data?	Kinematic, kinetic, balance data?	Athletic performance test data?
Sportsmetrics [2–17]	60–90 min, 3×/wk for 6 wk preseason	Plyometrics, strength, flexibility (Chap. 17) Volleyball, basketball, soccer, tennis-specific exercises added for agility, speed, and endurance (Chap. 18)	Yes	Yes	Yes
Prevent Injury and Enhance Performance Program (PEP) [18–23]	20-min warm-up in-season	Running, flexibility, strength, plyometrics, agility (Table 20.3)	Yes	Yes	Yes
Knee Ligament Injury Prevention Program (KLIP) [24, 25]	20-min warm-up, 2×/wk in-season	Plyometrics, agility (Table 20.7)	Yes	Yes	Yes
International Football Federation (FIFA) "11" [26];	20-min warm-up, 15 consecutive sessions, then 1×/wk in-season	Core, balance, plyometrics, strength (Table 20.5)	Yes	No	No
FIFA 11+ (also known as F-MARC 11+) [27, 28]	15-min warm-up, 3×/wk for 10wk in-season; 20-min warm-up, all practices in-season	Running, strength, plyometrics, balance (Table 20.10)	No	Yes	Yes
Myklebust [29, 30]	15-min warm-up, 3×/wk for 5–7 wk, then 1×/wk in-season	Floor, mat, wobble board (Table 20.9)	Yes	Yes	Yes
Petersen [31]	10-min warm-up, 3×/wk for 8 wk, then 1×/wk in-season	Balance, plyometrics (Table 20.8)	Yes	No	No
Pasanen [32, 33]	20–30-min warm-up, 2–3×/wk in-season	Running, balance, plyometrics, strength (Table 20.6)	Yes	No	Yes
Knee Injury Prevention Program (KIPP) [34]	20-min warm-up before practice in-season	Plyometrics, strength, agility (Table 20.14)	Yes	No	No
HarmoKnee [35]	20–25-min, 2 x/wk preseason, 1 x/wk in-season	Plyometrics, strength, core stability (Table 20.5)	Yes	No	No
Walden (Knäkontroll, SISU Idrottsböcker, Sweden) [36–39]	15-min warm-up, 2×/wk in-season	Plyometrics, strength	Yes	Yes	Yes
Myer [40–47]	90 min, 3×/wk for 6 wk	2 programs: plyometric or balance and dynamic stabilization	No	Yes	Yes

Table 21.1 (continued)

Program or author (citation)	Program duration	Program components	ACL injury rate calculated by exposure data?	Kinematic, kinetic, balance data?	Athletic performance test data?
Lephart [48]	30 min, 3×/wk for 8 wk	2 programs: plyometric (flexibility, balance, strength, agility), basic (flexibility, balance, strength)	No	Yes	Yes
Kerlan-Jobe [49]	10–15-min warm-up, 6×/wk for 6 wk in-season or preseason	Strength, balance, plyometrics (Table 20.12)	No	Yes	Yes
Herman [50, 51]	45 min, 3×/wk for 9 wk	Strength training, resistance bands, exercise balls Feedback in 1 group, 3 sessions, video landing technique analyzed	No No	Yes Yes	Yes Yes
Oslo Sports Trauma Research Center [52, 53]	20-min warm-up, 2×/wk for 18 wk in-season	Balance, agility, plyometrics, strength	No	Yes	Yes
Herrington [54]	15 min, 3×/wk for 4 wk	Plyometrics	No	Yes	Yes
DiStefano [55]	10–15-min warm-up, 3–4×/wk in-season	2 programs: 1 general, 1 designed on performance on squat test (Table 20.13)	No	Yes	No
Sportsmetrics plyometrics only [56]	60 min, 3×/wk for 8 wk	Plyometrics	No	Yes	Yes
Functional Stabilization Training [57]	80 min, 3×/wk for 8 wk	Hip and core strengthening	No	Yes	Yes
Hurd [58]	60 min, 10 sessions over 3–4 wk	Perturbation on balance board, strength, agility	No	Yes	No
Kato [59]	20 min, 3×/wk for 4 wk during practice	Strength, plyometrics, balance	No	Yes	No
McLeod [60]	90 min, 2×/wk for 6 wk in-season	Strength, plyometrics, agility, balance	No	Yes	No
Wilderman [61]	15 min, 4 x/wk for 6 wk in-season	Agility drills	No	Yes	No
Nagano [62]	20 min, 3×/wk for 5 wk	Plyometrics, balance	No	Yes	No
Pfile [63]	20 min, 3×/wk for 4 wk	Plyometrics or core stability exercises	No	Yes	No
Steib [64]	15-min warm-up, 3×/wk for 11 wk	Strength, balance, plyometrics	No	Yes	No
Weltin [65]	20–40 min, 3×/wk for 4 wk in-season	Plyometrics only or plyometrics and lateral reactive jumps with perturbation	No	Yes	No
Hopper [66]	60 min, 3×/wk for 6 wk during season	Plyometrics, resistance strength	No	Yes	No

(continued)

Table 21.1 (continued)

Program or author (citation)	Program duration	Program components	ACL injury rate calculated by exposure data?	Kinematic, kinetic, balance data?	Athletic performance test data?
Letafatkar [67]	60 min, 3×/wk for 6 wk	Perturbation drills	No	Yes	No
Ericksen [68]	15 min, 3×/wk for 4 wk	Plyometrics	No	Yes	No
Brown [69]	3 different programs, 20–60 min 3×/wk for 6 wk	Sportsmetrics, plyometrics only, or core stability/balance only	No	Yes	No
Stearns [70]	30 min, 3×/wk for 4 wk	Plyometrics, balance	No	Yes	No

athlete's age and sport. Can a program that is successful in adolescent soccer players has similar outcomes in adult handball players? A third issue is whether athletes identified as having a high risk of sustaining a noncontact ACL injury should undergo a different training program than those who are believed to be at a lower risk for this injury. The difficulty with this issue is that there does not exist to date a comprehensive model that predicts ACL injury risk according to all of the potential risk factors: anatomical, environmental, hormonal, neuromuscular, familial, playing surface, equipment, cardiovascular conditioning, and nutrition.

Multiple meta-analyses [78–84] that assessed the ability of neuromuscular training programs to reduce ACL injury rates concluded that these intervention programs were indeed effective. However, these studies combined data from very different types of training programs and did not answer the major issues discussed above. Systematic reviews (that did not combine data of programs) have reported that, while some programs are effective, others do not significantly reduce the risk of ACL injury and stress the importance of understanding the variation in training protocols and study design in ascertaining the differences in outcomes [7, 85–87].

There are important qualifiers in the studies included in this chapter. First, nearly all of the investigations analyzed preplanned tasks in a controlled laboratory setting. The effectiveness of these types of programs in improving potentially deleterious neuromuscular indices under reactive, unplanned athletic conditions is unknown. Secondly, few studies provided effect sizes (ES) in addition to *P* values when reporting effects of training [10–12, 17, 61, 69]. The ES measures the magnitude of the effects of treatment and is especially relevant in studies with small sample sizes [88]. It is probable that some statistically significant findings ($P < 0.05$) reported in the studies in this chapter may have limited clinical relevance. A third qualifier is that few studies conducted a prospective power calculation of the sample size required to discern a detectable difference (95% CI) in knee and hip kinetic and kinematic factors resulting from the training program [4, 9, 11, 15, 19, 42, 44, 52, 68–70]. Finally, the determination of the magnitude of change required to actually reduce the risk of an ACL injury in knee and hip kinetic and kinematic factors remains unknown and is speculative at best.

The goals of this chapter are to review the current available data regarding the outcome of ACL intervention programs on the reduction of noncontact ACL injuries, improvement of neuromuscular deficiencies or at-risk body positions and movements, and enhancement of athletic performance indices in female athletes. This chapter serves to summarize the data, and the reader is referred to other chapters for further detail regarding these outcomes. Only programs that focused on adolescent or adult female athletes are included.

Critical Points

- More than 30 ACL intervention programs are published.
- Differences exist regarding frequency, intensity, duration, and components.
  - Effectiveness of warm-up programs
  - Modified according to age
  - Identification of at-risk athletes
- Chapter summarizes data on ability of programs to:
  - Reduce ACL noncontact injury rate
  - Improve neuromuscular deficiencies
  - Improve athletic performance indicators

21.2 Reducing the Incidence of Noncontact ACL Injuries

Ten intervention studies to date have reported noncontact ACL injury rates in female athletes according to athlete exposures (AE; Table 21.2) [7, 18, 20, 25, 26, 31, 32, 34, 35, 39]. Several other studies that reported data on intervention programs either did not provide ACL injury rates according to AE or did not indicate if the ACL injuries were noncontact in nature and are not included [1, 27, 30, 37, 89–92]. In addition, injury intervention studies that focused only on male athletes are not included in this review [88, 93, 94, 101].

Three programs—Sportsmetrics, Prevent Injury and Enhance Performance (PEP) program, and Knee Injury Prevention Program (KIPP)—statistically reduced the noncontact ACL injury rate [7, 20, 34]. Sportsmetrics was conducted in 700 high school female athletes before the start of the athletic season (see Chap. 17). The results from the trained athletes and 1120 control athletes demonstrated ACL injury rates of 0.03 and 0.21 per 1000 AE, respectively ($P = 0.03$). The PEP program was conducted in 1885 high school female soccer players over the course of one season (see also Chap. 20, Table 20.3) [20]. A significant reduction was reported in the noncontact ACL injury incident rate between the trained and 3818 control players (0.09 and 0.49 per 1000 AE, respectively, $P < 0.0001$). KIPP training was conducted in 485 high school female basketball and soccer players before practices over the course of one season (see also Chap. 20, Table 20.4) [34]. A significant decrease was found in the noncontact injury incident rate between the trained and 370 control players (0.10 and 0.48 per 1000 AE, respectively, $P = 0.04$).

Several studies [18, 25, 26, 30–32, 35, 39] reported that other intervention programs failed to have an effect on reducing ACL injury rates. Issues pertaining to poor compliance with training and a small number of noncontact ACL injuries were commonly cited as the reasons for the outcomes of these investigations. In general, ACL intervention programs published to date have had multiple methodological problems which preclude definitive answers regarding which programs are effective and which are ineffective. The lack of randomization and control, limited statistical power due to small number of exposures and ACL injuries, failure to determine ACL injury incidence according to AE, poor compliance with training, poor documentation of contact versus noncontact ACL injuries, and changes in study protocols over the course of investigations were found. Even with these acknowledged problems, recent conference and committee statements [95–97] have concluded that neuromuscular retraining can reduce the incidence of noncontact ACL injuries in female athletes. The International Olympic Committee current concepts statement [98] is shown below:

1. The program should include strength and power exercises, neuromuscular training, plyometrics and agility exercises.
2. Design as a regular warm-up program to increase adherence.
3. Focus should be on performance of the hip-knee-foot line and “kissing knees” should be avoided (excessive valgus strain).
4. Maintenance and compliance of prevention program before, during and after the sports participation season are essential to minimize injuries.
5. The drop vertical jump test should be used to identify players at risk.

Table 21.2 Effect of intervention programs on ACL noncontact injury rates in female athletes according to athlete exposures

Program or author (citation)	No. female athletes, sports	No. athlete exposures		No. ACL noncontact injuries (per 1000 athlete exposures)			Comments, study limitations
		Trained	Control	Trained	Control	*P* value	
Sportsmetrics [7]	700 trained, 1120 control High school team sports	36,724	61,244	1 (0.03)	13 (0.21)	0.03	Not randomized or double-blinded, low no. noncontact ACL injuries
KIPP [34]	485 trained, 370 control High school soccer, basketball	20,345	12,467	2 (0.10)	6 (0.48)	0.04	Injuries not sorted according to sport, only 37% of coaches invited participated
PEP [20]	1885 trained, 3818 control High school soccer	67,860	137,448	6 (0.09)	67 (0.49)	<0.0001	Not randomized
PEP [18]	583 trained, 852 control Collegiate soccer	35,220	52,919	2 (0.057)	10 (0.189)	NS	Low no. noncontact ACL injuries
Walden [39]	2479 trained, 2085 control Adolescent soccer	149,214	129,084	5 (0.03)	7 (0.05)	NS	Low attendance rates, low no. noncontact ACL injuries
HarmoKnee [35]	777 trained, 729 control High school soccer	66,981	66,505	0	5 (0.07)	NS	Not randomized, low no. noncontact ACL injuries
FIFA "11" [26]	1073 trained, 947 control High school soccer	66,423	65,725	3 (0.05)	2 (0.03)	NS	Poor compliance with training, low no. noncontact ACL injuries
Pasanen [32]	256 trained, 201 control Adult floorball	32,327	25,019	6 (0.18)	4 (0.16)	NS	Low no. noncontact ACL injuries
KLIP [25]	577 trained, 862 control High school soccer, basketball, volleyball	17,954	38,662	3 (0.17)	3 (0.08)	NS	Not randomized, low no. noncontact ACL injuries
Petersen [31]	134 trained, 142 control Team handball	NA	NA	0	5 (0.21)	NS	Not randomized, low no. noncontact ACL injuries

FIFA International Football Federation, *NS* not significant, *PEP* Prevent Injury and Enhance Performance Program, *KLIP* Knee Ligament Injury Prevention Program, and *KIPP* Knee Injury Prevention Program

Table 21.3 Effect of ACL intervention training on landing forces

Program or author (citation)	Subjects[a]	Tests	Landing forces
Sportsmetrics [2]	11 trained females, 9 control male High school volleyball	Vertical jump	Decreased landing forces mean 456 N ($P = 0.006$, ES = NA)
KLIP [24]	14 trained, 14 control College students	Step-land	Reduced peak vertical ground reaction forces from 5.3 ± 1.0 to 3.9 ± 0.6 BW ($P = 0.0004$, ES = NA), rate force development from 0.11 ± 0.03 to 0.08 ± 0.02 BW/meters per s ($P = 0.02$, ES = NA)
Herman [50]	29 trained strength, feedback 29 feedback only 18–30 y Recreational athletes	Stop-jump	All subjects combined decreased peak vertical ground reaction forces from 1.61 ± 0.64 to 1.26 ± 0.41 × BW ($P < 0.001$, ES = NA)
Ericksen [68]	32 trained, 16 control College students	Rebound jump-land	Decreased peak vertical ground reaction forces mean − 0.5 ± 0.2 N/kg ($P < 0.001$, ES = NA)
Myer [42]	18 trained High school athletes	Single-leg hop	Balance trained group decreased impact forces 7.0%, plyometric trained group increased forces 7.6% (difference between groups $P < 0.05$, ES = NA)
Sportsmetrics [15]	10 trained, 10 control College intramural basketball	Vertical jump	No improvement
Sportsmetrics [17]	11 trained, 8 control College basketball	Forward lunge, unilateral step-down	No improvement
Lephart [48]	27 trained High school athletes	Vertical jump	No improvement
Kerlan-Jobe [49]	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	No improvement
Herman [51]	33 trained, 33 control 18–30 years Recreational athletes	3 stop-jump tasks	No improvement
Wilderman [61]	15 trained, 15 control College intramural basketball	Side-step pivot	No improvement

BW body weight, *ES* effect size, *KLIP* Knee Ligament Injury Prevention Program, *MS* milliseconds, *NA* not assessed
[a] Female subjects unless otherwise indicated

6. The program must be well received by coaches and players to be successful.
7. Evaluation of success or failure of a prevention program requires large numbers of athletes and injuries.

The American Academy of Pediatrics issued the following three-part policy statement in 2014 regarding ACL injury prevention training [96]:

- Neuromuscular training appears to reduce the risk of injury in adolescent female athletes by 72%. Prevention training that incorporates plyometric and strengthening exercises, combined with feedback to athletes on proper technique, appears to be most effective.
- Pediatricians and orthopedic surgeons should direct patients at highest risk of ACL injuries (e.g., adolescent female athletes, patients with previous ACL injury, generalized ligamentous laxity, or family history of ACL injury) to appropriate resources to reduce their injury risk (http://www.aap.org/cosmf). Such discussions also should be appropriately documented in the patient's medical record.

Table 21.4 Effect of ACL intervention training on knee and hip moments

Program	Subjects[a]	Tests	Knee moments	Hip moments
Sportsmetrics [2]	11 trained, 9 control males High school athletes	Vertical jump	Decreased abduction from 3.4 to 2.1% BW × Ht ($P < 0.05$, ES = NA), adduction 4.0 to 1.9% bw × ht ($P < 0.05$, ES = NA) No improvement extension, flexion moments	No improvement abduction, adduction or flexion, extension moments
Myer [45]	41 trained, 12 control High school athletes	Drop-jump	Decreased varus from 34.0 ± 2.8 to 21.1 ± 1.7 Nm, valgus from 60.4 ± 5.5 to 43.4 ± 3.3 Nm right knee ($P < 0.001$, ES = NA) No effect varus, valgus moments left knee	NA
Myer [43]	18 trained High school athletes	Drop-jump	12 athletes with >25.25 Nm abduction moment significantly reduced ($P = 0.03$, ES = NA) 6 athletes with <25.25 Nm abduction moment did not improve	NA
Lephart [48]	27 trained High school athletes	Vertical jump	Decreased peak flexion 0.076 ± 0.038 to 0.059 ± 0.01 Nm/bw × ht. ($P = 0.01$, ES = NA) No effect peak valgus moment	Decreased flexion 0.170 ± 0.058 to 0.153 ± 0.033 Nm/bw × ht. ($P = 0.008$, ES = NA) No effect peak adduction moment
Kerlan-Jobe [49]	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	Drop-jump: decreased maximum flexion from 0.739 ± 0.37 to 0.583 ± 0.30 Nm ($P = 0.04$, ES = NA), external rotation from −0.032 ± 0.12 to 0.027 ± 0.10 Nm ($P = 0.03$, ES = NA) No effect valgus moments Stop-jump: decreased valgus from 0.863 ± 0.37 to 0.734 ± 0.31 Nm ($P = 0.04$, ES = NA) No effect flexion, external rotation moments	Drop-jump: no improvement peak flexion, abduction, or external rotation moments Stop-jump: no improvement peak flexion, abduction, or external rotation moments
Herman [50]	29 strength and feedback trained 29 feedback trained 18–30 y Recreational athletes	Stop-jump	Decreased valgus from 0.107 ± 0.060 to 0.064 ± 0.038 Nm/bw × ht ($P < 0.0001$, ES = NA) No improvement extension moment	Decreased adduction from 0.115 ± 0.064 to 0.035 ± 0.130 Nm/bw × ht ($P < 0.0001$, ES = NA)
Pfile [63]	9 plyometric trained 9 core stability trained 6 controls High school athletes	Drop-jump	Plyometric: decreased flexion mean − 0.33 ± 0.04 (P = NA, ES = 2.04), valgus 0.09 Nm/kg-m (P = NA, ES = 1.52) Core stability: no change	Plyometric: no change Core stability: decreased flexion −0.33 ± 0.05 (P = NA, ES = 1.51), internal rotation −0.06 ± 0.01 Nm/kg m (P = NA, ES = 2.21)

Table 21.4 (continued)

Program	Subjects[a]	Tests	Knee moments	Hip moments
Weltin [65]	12 perturbation and perturbation trained 12 plyometric only trained Soccer, handball, basketball players	Lateral jump, cut, both reactive	Both groups decreased flexion ($P < 0.05$, ES = 0.20) and internal rotation moments ($P < 0.001$, ES = 0.47) lateral jump No improvement cut	NA
Stearns [70]	21 trained Recreational athletes 18–25 y	Drop-jump	Decreased adductor moments from 0.06 ± 0.1 to −0.02 ± 0.1 Nm/dg ($P < 0.001$, ES = NA)	Increased extensor moment from 0.92 ± 0.2 to 1.10 ± 0.2 ($P = 0.002$, ES = NA)
Ericksen [68]	32 trained, 16 control College students	Rebound jump-land	No improvement	No improvement
Brown [69]	30 trained 3 different programs, 13 control 13–18 years athletes	Jump-land single and double-leg	No improvement	No improvement
Herman [51]	33 trained, 33 control 18–30 y Recreational athletes	3 stop-jump tasks	No improvement extension or valgus moments	No improvement adduction or internal rotation moments
PEP, modified [19]	11 trained, 11 control High school basketball	Rebound jump	No improvement valgus moment	NA

BW body weight, *ES* effect size, *FIFA* International Football Federation, *HT* height, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program

[a]Female subjects unless otherwise indicated

- Pediatricians and orthopedic surgeons who work with schools and sports organizations are encouraged to educate athletes, parents, coaches, and sports administrators about the benefits of neuromuscular training in reducing ACL injuries and direct them to appropriate resources (http://www.aap.org/cosmf).

The ability of neuromuscular retraining programs to reduce the incidence of noncontact ACL injuries in female athletes is most likely due to the increased awareness of injury situations and changes in neuromuscular indices that improve balance, strength, and coordination; provide for safer landing, pivoting, and cutting techniques; increase joint stabilization; and enhance muscular preactivation and reactive patterns to be discussed next.

Critical Points

- Ten studies reported ACL injury rates according to athlete exposures in females:
  - Three significantly reduced ACL noncontact injury rates: Sportsmetrics, PEP, and KIPP.

- Others failed to reduce ACL noncontact injury rates:
  Poor compliance with training
  Too few ACL injuries, limited statistical power
  Lack of randomization
  Changes intervention protocols over time

21.3 Changes in Knee and Hip Kinetics and Kinematics

A wide variety of studies have been published to date which analyzed the effectiveness of knee injury prevention programs in changing kinematic or kinetic factors in female athletes [2, 4, 9–12, 15, 17, 19, 21, 24, 42–45, 48–55, 59, 61, 62, 68–70].

21.3.1 Landing Forces

Statistically significant decreases in landing forces from a vertical jump [2], step-land [24], single-leg hop [42], rebound jump-land [68], and stop-jump [50] have been reported following neuromuscular training (Table 21.3). A mean reduction of 456 N (103 pounds, 46.72 kg) during a vertical jump was reported after Sportsmetrics training [2] in female high school volleyball players (Fig. 21.1). Another study [50] reported a mean reduction of 22% during a stop-jump task after training in recreational female athletes 18–30 years of age. One study reported decreases in impact forces on a single-leg hop in a group of patients who completed a balance training program; however, a group that completed a plyometrics training program demonstrated increases in impact forces [42]. None of these studies reported ES.

In contrast, no reduction in landing forces were reported in several other investigations. These included tests involving a unilateral step-down or forward lunge [17], a vertical jump [15, 48], a drop-jump and vertical stop-jump [49], three stop-jump tasks [51], and a side-step pivot [61]. In five of these six studies, the populations under investigation were collegiate or recreational athletes ≥18 years old. Factors believed to affect the ability of ACL intervention programs to alter landing forces include age (young versus adult), athletic experience (competitive versus recreational), type of instruction, and exercise protocol [15].

Fig. 21.1 Vertical jump test on force plate

21.3.2 Knee and Hip Moments

Statistically significant decreases in potentially deleterious moments have been noted during planned tasks such as a vertical jump or drop-jump by several investigations after ACL intervention training (Table 21.4) [2, 43, 45, 48–50, 63, 65, 70]. The Sportsmetrics training program produced significant decreases in knee abduction and adduction moments on a vertical jump [2]. A similar training program resulted in significant decreases in knee internal valgus (abduction) moments of 28% and internal varus (adduction) moments of 38% on a drop-jump test [43]. A program performed in collegiate soccer and basketball players produced mixed results in terms of reduction of potentially harmful moments [49]. Statistically significant decreases in knee external rotation moments and knee flexion moments were found on a drop-jump test. However, there were no effects on hip external rotation, abduction, or flexion moments or knee valgus moments on this test. ES were not reported in any of these studies.

One study compared the effects of a 4-week core stability program with a plyometric program in knee and hip moments on a drop-jump in a small group of high school athletes [63]. In the plyometric group, significant decreases and moderate ES were noted in knee flexion and knee valgus moments. There were no changes in hip flexion or internal rotation moments. In the core stability group, significant decreases and large ES were noted in hip flexion and hip internal rotation moments; however, no changes were reported in knee moments. Another study found that either plyometric training or plyometric training combined with perturbation techniques significantly decreased knee flexion and internal rotation moments on a reactive lateral jump, with large ES noted [65]. There were no effects of either training protocol in reducing knee moments on a reactive cutting task.

21.3.3 Knee and Hip Flexion Angles

Increases in knee flexion angles on landing from various tasks following ACL intervention training have been demonstrated in several studies, although the data vary in regard to the magnitude of change and whether the improvements occurred at foot strike or during the deepest point of the land, indicated as maximum or peak knee flexion (Table 21.5) [19, 42, 44, 45, 48–50, 55, 62, 67–70]. Slight average increases in knee flexion at foot strike of 5.2° [49] and 5.8° [44] during a drop-jump test were reported in two studies, and a mean increase of 4.9° on a single-leg drop landing was found in another study [62]. One study reported a mean increase of 6.2° in knee flexion (ES 0.83) on a two-legged landing after completion of a standard neuromuscular training program [69]. However, there was no improvement in a single-leg landing task. Several other studies failed to observe an improvement in knee flexion at either foot strike or the maximum point of the landing during a variety of tasks [2, 21, 51, 53, 56, 57, 59, 61, 63]. One study found a concerning significant decrease in knee flexion after completion of either a plyometric or a core stability program [63]. The plyometric group had a mean decrease of 18.5 ± 3.6° (ES 1.79), and the core group had a mean decrease of 16.3 ± 3.4° (ES 1.88).

Several studies [21, 44, 48–50, 56, 57, 68–70] have reported statistically significant improvements in either hip flexion, abduction, adduction, external rotation, or internal rotation (Table 21.5). However, several others [2, 51, 53, 63] failed to find improvements in hip angles after intervention training.

One study of 30 athletes reported a mean increase of 8.2° in hip flexion (ES 0.52) on a two-legged landing after completion of a standard neuromuscular training program [69]. However, there was no improvement in a single-leg landing task. This was the only study located that included ES in the analysis of hip flexion angles. Increases in initial and peak hip flexion during a vertical jump were described in one study following plyometric training [48]. However, there were no improvements for initial or peak hip abduction or adduction angles. Another investigation reported significant increases in maximum hip flexion and abduction angles on a stop-jump task [50]. Significant decreases in mean hip internal rotation and increases in mean hip abduction were noted during a drop-jump test following the PEP training program [21]. One study described significant decreases in hip flexion at foot strike and in maximal hip external rotation on a stop-jump task [49].

Table 21.5 Effect of ACL intervention training on knee and hip flexion angles

Program	Subjects[a]	Tests	Knee angles	Hip angles
Myer [45]	41 trained, 12 control High school athletes	Drop-jump	Increased total flexion-extension on landing from 71.9 ± 1.4 to 76.9 ± 1.4° (right knee) and from 71.3 ± 1.5 to 77.3 ± 1.4° (left knee) ($P < 0.001$, ES = NA)	NA
Myer [42, 44]	8 trained plyometric 10 trained balance High school athletes	Drop-jump, single-leg medial drop-land, single-leg hop	Drop-jump: Plyo group increased flexion initial contact from 29.8 ± 6.6 to 35.6 ± 7.5°, peak from 93.4 ± 54.2 to 101.6 ± 50.5° ($P < 0.05$, ES = NA) No change abduction Medial drop: Balance group increased peak flexion ($P = 0.005$, ES = NA). Both groups decreased abduction initial contact and peak ($P = 0.04$, ES = NA)	Drop-jump: both groups decreased adduction at initial contact from −4.6 to −5.7°, peak from −2.1 to −3.4° ($P = 0.015$, ES = NA) Medial drop: No change adduction
Lephart [48]	27 trained High school	Vertical jump	Improved peak flexion from 62.2 ± 9.7 to 86.0 ± 35.1° (plyometric group), from 63.0 ± 18.1 to 70.9 ± 19.7° (basic training group) ($P < 0.01$, ES = NA), time to peak ($P = 0.006$, ES = NA) No change flexion at initial contact	Improved flexion initial contact from 1.9 ± 5.3 to 9.7 ± 8.7° ($P = 0.02$, ES = NA), peak from 19.6 ± 9.3 to 27.2 ± 10.5° ($P = 02$, ES = NA) No change initial contact or peak for abduction, adduction
PEP [21]	18 trained High school soccer	Drop-jump	No change peak flexion	Reduced peak internal rotation from 7.1 to 1.9° ($P = 0.01$, ES = NA), increased abduction from −4.9 to −7.7° ($P = 0.02$, ES = NA)
PEP, modified [19]	11 trained, 11 control High school basketball	Rebound jump	Increased peak flexion from 92.66 ± 4.34 to 94.27 ± 3.44° ($P = 0.02$, ES = NA) No change peak internal tibial rotation	NA
Kerlan-Jobe [49]	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	Drop-jump: Increased flexion foot strike from 29.9 ± 9.0 to 35.1 ± 7.4° ($P = 0.003$, ES = NA), stance phase from 81.3 ± 10.5 to 86.9 ± 10.3° ($P = 0.006$, ES = NA) Stop-jump: No change flexion at foot strike or stance phase, no change internal tibial rotation	Drop-jump: No change flexion, abduction, external rotation at foot strike or peak Stop-jump: Decreased flexion foot strike from 72.2 ± 11.0 to 68.0 ± 8.9°, ($P = 0.05$, ES = NA), peak external rotation from 20.0 ± 12.5 to 13.1 ± 13.8° ($P = 0.02$, ES = NA) No change abduction or internal rotation
DiStefano [55]	83 trained females 90 trained males Soccer 10–17 y	Drop-jump	Improved flexion foot strike ($P = 0.009$, ES = NA) (data not provided)	NA

Table 21.5 (continued)

Program	Subjects[a]	Tests	Knee angles	Hip angles
Herman [50]	29 trained strength and feedback 29 trained feedback 18–30 y Recreational athletes	Stop-jump	All subjects combined increased peak flexion from 27.20 ± 7.02 to 28.96 ± 5.23° ($P = 0.05$, ES = NA)	All subjects combined increased max flexion angle from 44.77 ± 10.96 to 51.80 ± 8.91° ($P < 0.001$, ES = NA), abduction angle from 8.88 ± 5.88 to 11.31 ± 8.72° ($P = 0.03$, ES = NA)
Herman [51]	33 trained, 33 control 18–30 years Recreational athletes	3 stop-jump tasks	No change peak flexion	No change peak flexion
Nagano [62]	8 trained College basketball	Single-leg drop landing	Increased flexion initial foot contact from 19.3 ± 2.5 to 24.2 ± 2.1° ($P < 0.01$, ES = NA), peak from 34.3 ± 2.5 to 40.2 ± 1.9° ($P < 0.001$, ES = NA) No change external or internal tibial rotation	NA
Letafatkar [67]	15 trained, 14 control Collegiate athletes	Drop-jump	Increased flexion initial contact ($P = 0.001$, ES = 0.4) and peak ($P = 0.001$, ES = 0.9)	NA
Ericksen [68]	32 trained, 16 control College students	Rebound jump-land	Increased peak flexion mean 11.3 ± 10.4° ($P < 0.001$, ES = NA)	Increased peak flexion mean 10.9 ± 9.4° ($P = 0.001$, ES = NA)
Brown [69]	30 trained 3 different programs, 13 control 13–18 years athletes	Jump-land single and two legged	Standard program: increased peak flexion mean 6.2° ($P < 0.05$, ES = 0.84) bilateral landings. No improvement single-leg landings	Standard program: increased peak flexion mean 8.2° ($P = 0.01$, ES = 0.52) bilateral landings. No improvement single-leg landings
Stearns [70]	21 trained Recreational athletes 18–25 years	Drop-jump	Increased peak flexion from 94.0 ± 8.5° to 98.0 ± 10.1° ($P < 0.001$, ES = NA)	Increased from 83.4 ± 7.6° to 89.9 ± 8.8° ($P < 0.05$, ES = NA)
Sportsmetrics Plyometrics only [56]	18 trained, 18 control Recreational athletes 20 ± 1 years	Single-leg squat	Decreased knee abduction from −9.23 to −5.75° ($P = 0.01$, ES = NA)	Decreased hip adduction from 10.04 to 5.70° ($P < 0.001$, ES = NA)
Functional Stabilization Training [57]	14 trained, 14 control Recreational athletes 20 ± 1 years	Single-leg squat	Decreased knee abduction from −6.86 to 1.49° ($P < 0.001$, ES = NA)	Decreased hip adduction from 7.08 to 5.19° ($P < 0.05$, ES = NA)
Pfile [63]	9 plyometric trained 9 core stability trained 6 controls High school athletes	Drop-jump	Decreased flexion mean − 18.5 ± 3.6° plyometric group (P=NA, ES = 1.79), mean − 16.3 ± 3.4° core group (P = NA, ES = 1.88)	No change hip angles both groups

(continued)

Table 21.5 (continued)

Program	Subjects[a]	Tests	Knee angles	Hip angles
Sportsmetrics [2]	11 trained females 9 control males High school	Vertical jump	No change peak flexion	No change peak flexion
Kato [59]	10 trained, 10 control College basketball	Jump shot	No change peak flexion	NA
Oslo Sports Trauma Research Center [53]	20 trained Soccer, elite team handball Adults	Side-cut	No change peak flexion	No change peak flexion
Wilderman [61]	15 trained, 15 control College intramural basketball	Side-step pivot	No change flexion initial foot contact or peak	NA

ES effect size, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program
[a]Female subjects unless otherwise indicated

However, no significant differences were observed in hip kinematics on a drop-jump test.

21.3.4 Lower Limb Alignment

Multiple investigations have determined the effects of ACL intervention training on lower limb alignment during various jumping tasks (Table 21.6). The assessment involved either measuring the distance between the hips, knees, and ankles from a single-plane video analysis which provides a general indicator of overall lower limb alignment (absolute knee separation distance and normalized knee separation distance values, Fig. 21.2) or measuring varus-valgus angles in multiple planes.

Statistically significant improvements in knee separation distance following Sportsmetrics training have been noted by multiple studies [4, 8, 10–12]. The largest group followed (912 trained high school athletes) improved the absolute knee separation distance from 20 ± 8 cm to 27 ± 8 cm ($P < 0.0001$, ES 0.87) and the normalized knee separation distance from 47 ± 19% to 65 ± 18% ($P < 0.0001$, ES 0.97) [8]. Another group of high school female athletes improved knee separation distance a mean of 3.25 cm after completing the PEP program [19]. However, two other investigations failed to find significant improvements in lower limb alignment after participating in the PEP program [21, 22].

Only a few investigations reported improvements in knee valgus angles following training [54, 59], while several studies [21, 48–52, 55, 62, 68–70] found no training effects.

Critical Points

- Multiple studies have assessed changes in kinematic or kinetic factors in female athletes after training:
  - Landing forces (mixed results):
    May be affected by age, athletic experience, type of instruction, and exercise protocol
  - Moments:
    Majority studies decreased knee and hip moments

Table 21.6 Effect of ACL intervention training on lower limb alignment

Program	Subjects[a]	Tests	Lower limb alignment
Sportsmetrics [8]	1000 trained, 1120 control High school athletes	Drop-jump	Improved normalized knee separation distance from 47 ± 19 to 65 ± 18% ($P < 0.0001$, ES = 0.97), absolute knee separation distance from 20 ± 8 to 27 ± 8 cm ($P < 0.0001$, ES = 0.87)
Sportsmetrics Volleyball [10]	34 trained High school volleyball	Drop-jump	Improved normalized knee separation distance from 56.3 ± 19.1 to 63.3 ± 12.7% ($P = 0.04$, ES = 0.43), absolute knee separation distance from 21.1 ± 8.2 to 25.9 ± 5.2 cm ($P = 0.002$, ES = 0.70)
Sportsmetrics Volleyball [4]	16 trained High school volleyball	Drop-jump	Improved normalized knee separation distance immediately after training from 50 ± 16 to 67 ± 17% ($P < 0.01$, ES = NA) and 1 year later to 74 ± 17% ($P < 0.001$, ES = NA)
Sportsmetrics Basketball [11]	57 trained High school basketball	Drop-jump	Improved normalized knee separation distance from 44.9 ± 17.2 to 74.2 ± 18.8% ($P < 0.0001$, ES = 0.63), absolute knee separation distance from 18.5 ± 7.4 to 31.8 ± 10.36 cm ($P < 0.0001$, ES = 0.59)
Sportsmetrics Soccer [12]	62 trained High school soccer	Drop-jump	Improved normalized knee separation distance from 35.9 ± 7.4 to 54.2 ± 13.7% ($P < 0.0001$, ES = 0.64), absolute knee separation distance from 14.6 ± 3.6 to 23.1 ± 6.4 cm ($P < 0.0001$, ES = 0.63)
Kato [59]	10 trained, 10 control College basketball	Jump shot	Improved peak lower extremity angle in coronal plane from 36.9 ± 19.5 to 15.1 ± 6.5° ($P < 0.05$, ES = NA), torsion angle in horizontal plane from 22.5 ± 12.8 to 17.1 ± 4.6° ($P < 0.05$, ES = NA)
Herrington [54]	15 trained Adult elite basketball	Drop-jump, jump shot	Drop-jump: Decreased knee valgus angle, 9.8° left leg ($P = 0.002$, ES = NA), 12.3° right leg ($P = 0.0001$, ES = NA) Jump shot: Decreased knee valgus angle, 4.5° left leg ($P = 0.03$, ES = NA), 4.3° right leg ($P = 0.01$, ES = NA)
PEP, modified [19]	11 trained, 11 control High school basketball	Rebound jump	Improved knee separation distance from 17.56 ± 2.92 to 20.81 ± 1.37 cm ($P = 0.004$, ES = NA)
PEP [21]	18 trained High school soccer	Drop-jump	No change peak knee valgus angle
PEP [22]	20 trained Adult elite soccer	Drop-jump	No change knee separation distance
Lephart [48]	27 trained High school athletes	Vertical jump	No change knee valgus angle at foot strike or peak
Kerlan-Jobe [49]	30 trained College soccer, basketball	Drop-jump, vertical stop-jump	No change knee valgus angle at foot strike or peak
Herman [51]	33 trained, 33 control Recreational athletes 18–30 years	3 stop-jump tasks	No change peak knee valgus angle
Herman [50]	29 strength and feedback trained 29 feedback trained Recreational athletes 18–30 years	Stop-jump	No change peak knee valgus angle

(continued)

Table 21.6 (continued)

Program	Subjects[a]	Tests	Lower limb alignment
DiStefano [55]	83 trained females, 90 trained males Soccer 10–17 years	Drop-jump	No change knee valgus
Nagano [62]	8 trained College basketball	Single-leg drop landing	No change valgus angle at foot strike or peak
Oslo Sports Trauma Research Center [52]	20 trained, 20 control 15–16 years Soccer, handball	Side-cut	No change valgus angle at initial contact
Ericksen [68]	32 trained, 16 control College students	Rebound jump-land	No change knee abduction angle
Brown [69]	30 trained 3 different programs, 13 control 13–18 years athletes	Jump-land single and double legged	No change peak knee abduction angle
Stearns [70]	21 trained Recreational athletes 18–25 years	Drop-jump	No change peak knee abduction angle

ES effect size, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program; *WIPP* Warm-up for Injury Prevention and Performance

[a] Female subjects unless otherwise indicated

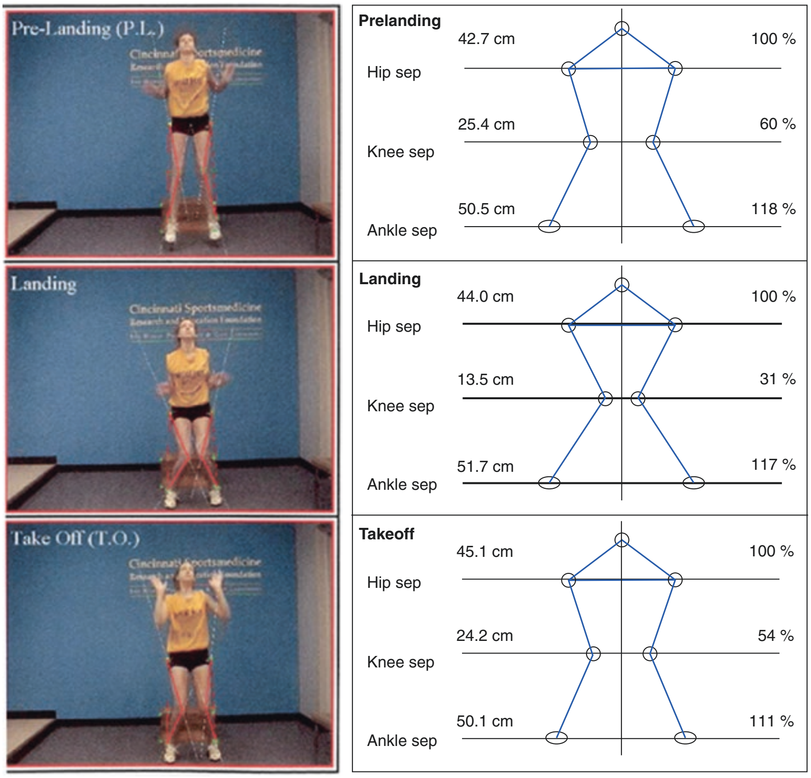

Fig. 21.2 Drop-jump video test. Three photographs are produced from the prelanding, landing, and take-off phases. The centimeters of distance between the hips, knees, and ankles are calculated along with normalized knee and ankle separation distances (according to the hip separation distance) using commercially available software (Cincinnati SportsMedicine Research and Education Foundation, Cincinnati, OH). Shown is the test result of a 16-year-old female subject before beginning the Sportsmetrics neuromuscular training program depicting poor knee separation distance and an obvious overall lower limb valgus alignment

- Knee flexion angles:
  Increased in several studies but varied in amount of change and when improvements occurred during tasks
- Hip flexion angles:
  Mixed results
- Lower limb alignment:
  Improved overall lower limb alignment in coronal plane in several studies on drop-jump test after Sportsmetrics training, but no change in knee valgus angles in multiple studies upon completion of other programs
- Several methodological problems found:
  Nearly all investigations analyzed preplanned tasks in a controlled laboratory setting.
  Few provided effect sizes or conducted prospective power analyses to determine adequate sample size.
- The determination of the magnitude of change required to actually reduce the risk of an ACL injury in knee and hip kinetic and kinematic factors remains unknown and is speculative at best.

21.4 Alterations in Lower Extremity Strength and Muscle Activation Patterns

A frequent finding among the studies included in this chapter was a statistically significant increase in lower extremity isokinetic (Fig. 21.3) or isometric strength (Table 21.7). Improvements in the strength of the hamstrings [2, 8, 9, 14, 17, 19, 22, 42, 50, 51, 57, 61, 62], quadriceps [8, 22, 48, 50, 51, 57, 99], gluteus maximum and medius [50, 51], hip abductors [19, 56, 70], and hip extensors [70] and in the hamstrings to quadriceps ratio [2, 8, 9, 14, 17, 19, 42] have been reported after 6–9 weeks of training. Only a few studies reported no improvements in muscle strength after training [13, 29, 77].

In addition, several studies [5, 16, 48, 52, 53, 58, 61, 62, 67] reported changes in electromyographic muscle activation patterns after ACL intervention training that appear to demonstrate an earlier onset of hamstrings activity, along with a reduction in quadriceps activity during drop-

Fig. 21.3 Isokinetic knee flexion-extension strength test on Biodex isokinetic dynamometer (Biodex Corporation, Shirley, NY)

Table 21.7 Effect of ACL intervention training on lower extremity strength, muscle activation patterns

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
Sportsmetrics [8]	1000 trained, 1120 control High school athletes	Isokinetic quadriceps, hamstring peak torque 300°/s	Increased hamstrings and quadriceps peak torque both legs ($P < 0.0001$, ES 0.27–0.61) and H:Q ratio both legs ($P < 0.01$, ES 0.27–0.34)	NA	NA
Sportsmetrics [16]	16 trained High school athletes	EMG during side-cut	NA	NA	10 ms post-land increased activation biceps femoris ($P < 0.01$, ES = 0.55), decreased medial hamstring to lateral hamstring co-contraction ratio
Sportsmetrics [13]	11 trained College basketball	Max voluntary isometric contraction H:Q ratio	NA	No improvement	NA
Sportsmetrics [17]	11 trained, 8 control College basketball	Isokinetic quadriceps, hamstring strength 60°/s, 300°/s	Improved hamstrings peak torque ($P = 0.008$, ES = NA) and H:Q ratio ($P = 0.04$, ES = NA) 60°/s. No effect hamstrings peak torque or H:Q ratio 300°/s. No effect quadriceps peak torque	NA	NA
Sportsmetrics [14]	11 trained, 14 control College students	Isokinetic quadriceps, hamstrings 60°/s, 120°/s	At 120°/s, improved hamstrings power from 30.76 ± 7.69 to 35.56 ± 7.92 ($P = 0.02$, ES = NA), peak torque from 24.71 ± 4.85 to 27.20 ± 5.16 ($P = 0.03$, ES = NA), H:Q ratio from 53.21 to 56.72 (P not given) No effect hamstrings power or peak torque 60°/s, quadriceps power or peak torque 60°/s or 120°/s	NA	NA
Sportsmetrics [5]	9 trained, 9 control Collegiate athletes	Drop-jump EMG analysis: preparatory, reactive phases	NA	NA	Increased hip adductor activity ($P < 0.05$, ES = NA), adductor-to-abductor muscle coactivation ($P = 0.04$, ES = NA) during preparatory phase. Improved H:Q coactivation ($P = 0.05$, ES = NA) reactive phase

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
Sportsmetrics Plyometrics only [56]	18 trained, 18 control recreational athletes 20 ± 1 years	Isokinetic eccentric quadriceps, hamstrings 60°/s; hip abductor, adductor, medial and lateral rotators 30°/s	Improved hip abductor, adductor, medial rotator peak torques. No effect quadriceps or hamstrings	NA	NA
Lephart [48]	27 trained High school athletes	Isokinetic quadriceps, hamstring peak torque 60°/s and 180°/s, isometric hip abduction peak torque, vertical jump	Improved quadriceps peak torque 60°/s and 180°/s ($P < 0.01$, ES = NA). No effect hamstrings peak torque	No improvement hip abduction peak torque	Earlier onset gluteus medius in plyometric group vs. strength group ($P < 0.05$, ES = NA), both groups greater gluteus medius preactivity ($P < 0.05$, ES = NA) Plyometric group reduced time to peak medial hamstring reactivity after foot strike ($P < 0.05$, ES = NA) No change vastus lateralis, lateral hamstring peak EMG preactivity or reactivity phases
Herman [51]	33 trained, 33 control 18–30 years Recreational athletes	Max voluntary isometric contraction	NA	Improved quadriceps, hamstrings, gluteus maximus, gluteus medius ($P < 0.001$, ES = NA)	NA

(continued)

Table 21.7 (continued)

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
Herman [50]	29 trained strength and feedback (ST-FB) 29 trained feedback 18–30 years Recreational athletes	Max voluntary isometric contraction	NA	Strength gains in ST-FB group for quadriceps, hamstrings, gluteus maximus, gluteus medius ($P < 0.001$, ES = NA)	NA
PEP [22]	20 trained Elite soccer 18.6 ± 2.7 years	Max voluntary isometric contraction quadriceps, hamstrings, gastrocnemius	NA	Improved quadriceps, hamstrings ($P < 0.001$, ES = NA)	NA
PEP, modified [19]	11 trained, 11 control High school basketball	Isokinetic quadriceps, hamstring, hip abduction, hip extension peak torque, power 60°/s	Improved peak torque, average power for all muscles tested ($P = 0.004$ to 0.04, ES = NA) and H:Q ratio. Decreased quadriceps torque ($P = 0.04$, ES = NA)	NA	NA
Wilderman [61]	15 trained, 15 control College intramural basketball	Max voluntary isometric contraction, side-step pivot	NA	NA	Increased medial hamstrings activation during loading phase ($P < 0.01$, ES = NA), decreased vastus medialis oblique activation. No effect lateral hamstrings activation
Stearns [70]	21 trained Recreational athletes 18–25 years	Max voluntary isometric contraction	NA	Increased hip extensors and hip abductors ($P = 0.01$, ES = NA)	NA

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
Hurd [58]	10 trained, 10 control males College athletes	Gait analysis, normal speed walk on perturbation platform	NA	NA	Before training, females' peak hamstring activity occurred after heel strike. After training, females had earlier onset time to peak hamstring activity (before heel strike), higher hamstrings activity, and reduced vastus lateralis activity
Oslo Sports Trauma Research Center [53]	20 trained Soccer, elite team handball, adults	Side-cut, EMG analysis	NA	NA	Greater semitendinosus muscle activity preland ($P < 0.01$, ES = NA) and land ($P < 0.05$, ES = NA) phases. Reduced activity gluteus medius preland ($P < 0.05$, ES = NA) and land ($P < 0.05$, ES = NA) phases. Reduced activity biceps femoris landing phase ($P < 0.01$, ES = NA). Reduced time to onset semitendinosus activity during preland phase ($P < 0.05$, ES = NA)
Oslo Sports Trauma Research Center [52]	20 trained, 20 control Collegiate soccer, handball	Side-cut, EMB analysis	NA	Increased hamstrings ($P = 0.01$, ES = NA)	Increased hamstrings preactivity ($P < 0.05$, ES = NA)
Nagano [62]	8 trained Collegiate basketball	Single-leg drop landing, max voluntary isometric contraction	NA	NA	Increased hamstring activity before foot strike ($P < 0.05$, ES = NA). No effect hamstring activity after foot strike. No differences rectus femoris activity, ham to quad ratio before or after foot strike
Myklebust [29]	27 trained Elite team handball, adult	Isokinetic quadriceps, hamstrings 60°/s, 240°/s	No improvement quadriceps, hamstrings, or H:Q ratio	NA	NA
Myer [42]	8 trained plyometric 10 trained balance High school athletes	Isokinetic quadriceps, hamstrings 300°/s	Improved hamstrings peak torque, H:Q ratio ($P < 0.01$, ES = NA)	NA	NA

(continued)

Table 21.7 (continued)

Program	Subjects[a]	Tests	Isokinetic strength	Isometric strength	EMG analyses
FIFA “11” [77]	17 trained, 14 control Soccer 16–18 years	Isokinetic quadriceps, hamstring peak torque 60°/s and 240°/s, isometric hip test	No improvement	No improvement hip abductors, adductors	NA
Functional Stabilization Training [57]	14 trained, 14 control Recreational athletes 20 ± 1 years	Isokinetic eccentric quadriceps, hamstrings 60°/s, hip abductor, adductor, medial, and lateral rotators 30°/s	Improved hip abductor, hip lateral rotator, hip medial rotator, knee flexor, knee extensor peak torques ($P < 0.001$, ES = NA)	NA	NA
Letafatkar [67]	15 trained, 14 control Collegiate athletes	Drop-jump, EMG analysis	NA	NA	Increased co-contraction quad to ham due to increased hamstring activity 0–50 ms and 50–150 ms after initial contact ($P = 0.001$, ES = 0.60–1.32)

ES effect size, FIFA, International Football Federation; *H:Q* hamstrings to quadriceps, *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program

[a] Female subjects unless otherwise indicated

jump, vertical jump, and side-cut activities. These alterations in muscle activation patterns are believed to be important in the prevention of ACL ruptures.

Critical Points

- Improved lower extremity muscle strength:
  - Hamstrings: ten studies
  - Quadriceps: five studies
  - Hamstrings to quadriceps ratio: six studies
- Improved hip muscle strength: two studies
- Muscle activation patterns:
  - Alterations in eight studies: earlier onset hamstrings activity, reduced quadriceps activity

21.5 Effect on Balance

Several studies have demonstrated improved balance following ACL intervention training programs (Table 21.8). The Star Excursion Balance Test has been used the most frequently to determine dynamic balance, with improvements found in reach distances in several studies [13, 40, 60, 64, 66].

Table 21.8 Effect of ACL intervention training on balance

Program	Subjects[a]	Tests	Results
Sportsmetrics [13]	11 trained College basketball	LESS, SEBT	Improved SEBT composite score ($P = 0.01$, ES = NA), LESS score ($P = 0.009$, ES = NA) immediately after training and 9 months later
Hopper [66]	13 trained, 10 control Netball, 12.17 ± 0.94 years	SEBT	Improved anterior, posteromedial, posterolateral directions ($P < 0.05$, ES = NA)
Steib [64]	21 trained, 20 control Handball, 24.0 ± 5.9 years	SEBT, single-leg stand for sway velocity	Improved all reach distances, significant differences compared with control group began at wk 6, largest differences at wk 11
Walden [38]	23 trained, 18 control 12–16 years soccer players	SEBT	No improvement
Filipa [40]	13 trained, 7 control High school soccer	SEBT	Improved SEBT composite ($P < 0.05$, ES = 0.13)
McLeod [60]	27 trained, 23 control High school athletes	BESS and SEBT	BESS: trained group fewer errors than pre-train and control group ($P = 0.03$, ES = NA) SEBT: improved anteromedial, medial, posterior, and lateral directions ($P < 0.001$, ES = NA)
Myer [47]	41 trained High school athletes	Biodex stability system: total stability index, anteroposterior stability index, medial-lateral stability index, single leg	Improved total stability ($P = 0.004$, ES = NA) and anteroposterior stability ($P = 0.001$, ES-NA)
Myklebust [29]	27 trained Elite team handball, adult	KAT 2000 balance index score single and two legs	Improved score for two legs ($P = 0.003$, ES = NA), no change single leg

BESS Balance Error Scoring System, *ES* effect size, *LESS* Landing Error Scoring System, *NA* not assessed, *SEBT* Star Excursion Balance Test

[a] Female subjects unless otherwise indicated

One study [47] involving high school athletes reported improvements in single-leg total stability and anteroposterior stability on the Biodex Stability System (Biodex Corporation, Shirley, NY, Fig. 21.4) after training. There was no improvement in medial-lateral stability in these subjects. Another investigation [60] found significant improvements in the Balance Error Scoring System, which is comprised of six different 20-s balance tests in different stances and on different surfaces. A group of 27 athletes who completed the training program had fewer errors than that recorded before training and also compared with a control group. These subjects also improved scores on the Star Excursion Balance Test in distances successfully reached with a single leg in anteromedial, medial, posterior, and lateral directions.

Fig. 21.4 Single-leg balance test on Biodex Stability System (Biodex Corporation, Shirley, NY)

Critical Point

- Improvements in Star Excursion Balance test reach distances found in several studies.

21.6 Enhancing Athletic Performance

There have been multiple studies which documented changes in athletic performance indicators following ACL injury prevention training in female athletes (Table 21.9) [5, 8, 10–12, 45, 49, 53, 54, 56, 57, 66]. Vertical jump height is one of the most common indices tested, with mixed results reported. Improvements have been noted in several studies, with mean published post-train increases ranging from 1.2 to 4 cm; however, most of the studies reported small ES [8, 10, 11, 45, 49, 53, 66]. Several other studies [12, 15, 19, 22–24, 32, 38, 77] found no significant increases in jump height after training.

Statistically significant increases in the distance hopped during various single-leg hop tests have been reported after training [8, 45, 49, 54, 56, 57]. In a study of 280 high school athletes, a mean increase in the triple crossover hop test of 33 ± 54 cm ($P < 0.0001$, ES 0.47) was found following Sportsmetrics training [8]. In a group of 18 recreational adult athletes, improvements in the triple hop test (mean, 43 cm, $P < 0.001$, ES not provided) were reported after 8 weeks of plyometric training [56]. Elite adult basketball players improved the distance on the triple hop test by a mean of 110–111 cm ($P = 0.001$, ES not provided) after 4 weeks of plyometric training [54].

Sprint times have been assessed in several investigations before and after training, with conflicting results reported. In a group of 221 high school athletes, the agility *T*-test time improved from 12.10 ± 1.01 s to 11.51 ± 0.83 s ($P < 0.0001$, ES 0.64) after Sportsmetrics training [8]. Similar findings were reported in 62 high school soccer players [12]. One study reported improvements in 10-m and 20-m sprints ($P < 0.05$, ES 1.2). However, several studies reported no improvements in sprint speed after training [5, 11, 23, 32, 38, 77].

Table 21.9 Effect of ACL intervention training on athletic performance

Program	Subjects[a]	Tests	Vertical jump	Single-leg hop tests	Speed, agility	VO$_2$max, core strength
Sportsmetrics [8]	1000 trained, 1120 control High school athletes	Vertical jump, single-leg triple hop and triple crossover hop, *t*-test, sprints, MSFT	Increased mean 1.3 cm ($P < 0.0001$, ES = small [value NA])	Increased triple crossover hop from 360 ± 71 to 393 ± 69 cm ($P < 0.0001$, ES = 0.47) right leg. Increased triple hop from 405 ± 96 to 414 ± 95 cm ($P = 0.003$, ES = 0.09) right leg	Improved t-test from 12.10 ± 1.01 to 11.51 ± 0.83 s ($P < 0.0001$, ES = 0.64)	Improved estimated VO$_2$max from 36.4 ± 5.0 to 39.2 ± 4.4 ($P < 0.0001$, ES = 0.57)
Sportsmetrics Volleyball [10]	34 trained Volleyball High school	Vertical jump, MSFT, sit-up test	Increased mean 1.2 cm from 40.1 ± 7.1 to 41.5 ± 4.5 cm ($P = 0.03$, ES = 0.24)	NA	NA	Improved estimated VO$_2$max from 39.4 ± 4.8 to 41.4 ± 4.0 ml/kg/min ($P < 0.001$, ES = 0.45) Increased sit-up from 37.7 ± 5.3 to 40.5 ± 5.9 reps ($P = 0.03$, ES = 0.50)
Sportsmetrics Basketball [11]	57 trained Basketball High school	Vertical jump, MSFT, 18.29-m sprint	Increased mean 2.3 cm, from 26.2 ± 12.3 to 28.5 ± 12 cm ($P < 0.0001$, ES = 0.09)	NA	No change	Improved estimated VO$_2$max from 34.6 ± 4.5 to 39.5 ± 5.7 ml/kg/min ($P < 0.0001$, ES = 0.43)
Sportsmetrics Soccer [12]	62 trained Soccer High school	Vertical jump, *t*-test, 37-m sprint, MSFT	Increased mean 1.3 cm, from 40.7 ± 8.9 to 42.1 ± 8.3 cm ($P = 0.04$, ES = 0.08)	NA	Improved t-test from 12.05 ± 0.87 to 11.31 ± 0.69 s ($P < 0.0001$, ES = 0.43) Improved 37-m sprint from 6.11 ± 0.43 s to 5.99 ± 0.38 s ($P = 0.02$, ES = 0.08)	Improved estimated VO$_2$max from 37.9 ± 4.5 to 40.1 ± 4.7 ml/kg/min ($P < 0.0001$, ES = 0.23)
Sportsmetrics Plyometrics only [56]	18 trained, 18 control recreational athletes 20 ± 1 years	Triple hop, 6-m timed hop	NA	Increased triple hop from 342 ± 51 to 385 ± 48 cm ($P < 0.001$, ES = NA), improved timed hop from 2.38 ± 0.33 s to 1.98 ± 0.28 s ($P < 0.001$, ES = NA)	NA	NA

(continued)

Table 21.9 (continued)

Program	Subjects[a]	Tests	Vertical jump	Single-leg hop tests	Speed, agility	VO_2max, core strength
Myer [45]	41 trained, 12 control High school athletes	Vertical jump, sprint 9.1-m, single-leg hop	Increased mean 3.3 cm, from 39.9 ± 0.9 to 43.2 ± 1.1 cm ($P < 0.001$, ES = NA)	Increased from 165.1 ± 3.0 to 175.5 ± 2.6 cm right leg, from 165.1 ± 2.7 to 173.6 ± 2.5 cm, left leg ($P < 0.001$, ES = NA)	Improved from 1.80 ± 0.02 to 1.73 ± 0.01 s ($P < 0.001$, ES = NA)	NA
Kerlan-Jobe [49]	30 trained College soccer, basketball	Vertical jump, timed single-leg hop	Increased mean 3.7 cm, from 45.1 ± 14.1 to 48.8 ± 13.9 cm ($P < 0.001$, ES = NA)	Improved from 2.17 ± 0.4 to 2.03 ± 0.3 s right leg, from 2.17 ± 0.4 to 2.0 ± 0.2 s left leg ($P < 0.001$, ES = NA)	NA	NA
Hopper [66]	13 trained, 10 control netball, 12.17 ± 0.94 years	Vertical jump, sprints, netball agility, netball movement	Increased mean 4 cm ($P < 0.05$, ES = 0.84)	NA	Improved 10-m, 20-m tests ($P < 0.05$, ES > 1.2), improved netball agility ($P < 0.05$, ES = 0.98) and movement ($P < 0.001$, ES = 2.7)	NA
Chimera [5]	9 trained, 9 control Collegiate athletes	Vertical jump, 36.57-m sprint	Improved 5.8% (mean 2.54 ± 2.97 cm, $P = 0.009$, ES = NA), but not significantly different from control group	NA	Improved, but not significantly different from control group	NA
Oslo Sports Trauma Research Center [53]	20 trained, 8 control Elite handball, soccer adult	Vertical jump	Increased from 27 ± 4 to 29 ± 4 cm ($P < 0.001$, ES = NA)	NA	NA	NA
Herrington [54]	15 trained Elite basketball 18–22 years	Single-leg triple crossover hop test	NA	Increased mean 111 cm left leg, 110 cm right leg ($P = 0.001$, ES = NA)	NA	NA
Functional Stabilization Training [57]	14 trained, 14 control Recreational athletes 20 ± 1 years	Triple hop, 6-m timed hop	NA	Increased triple hop from 352 ± 37 to 392 ± 43 cm ($P < 0.001$, ES = NA), improved timed hop from 2.43 ± 0.27 s to 2.14 ± 0.21 s ($P < 0.01$, ES = NA)	NA	NA

Program	Subjects[a]	Tests	Vertical jump	Single-leg hop tests	Speed, agility	VO_2max, core strength
PEP [23]	15 trained, 16 control Soccer Adolescents	Countermovement vertical jump, 9.1, 18.3, 27.4, 36.6-m sprints, Illinois agility, pro-agility	No change	NA	No change	NA
PEP [22]	20 trained Elite soccer 18.6 ± 2.7 years	Vertical jump	No change	NA	NA	NA
PEP, modified [19]	11 trained, 11 control High school basketball	Rebound jump	No change	NA	NA	NA
Panasen [33]	119 trained, 103 control Floorball teams	Vertical jump, figure-eight run	No change	NA	No change	NA
KLIP [24]	14 trained, 14 control College students	Vertical jump	No change	NA	NA	NA
FIFA "11" [77]	17 trained, 14 control Soccer players 16–18 y	Vertical jump, sprint running, soccer skill tests	No change	NA	No change	NA
Vescovi [15]	10 trained, 10 control College intramural basketball	Vertical jump	No change	NA	NA	NA
Walden [38]	12 trained, 18 control 12–16 years soccer players	Vertical jump, triple hop, sprints	No change	No change	No change	NA

ES effect size, *FIFA,* International Football Federation; *NA* not assessed, *PEP* Prevent Injury and Enhance Performance Program, and *KLIP* Knee Ligament Injury Prevention Program

[a] Female subjects unless otherwise indicated

Estimated VO_2max has been measured following Sportsmetrics training using the multistage fitness test [100]. One study [10] involving 34 female high school volleyball players reported a mean improvement following training from 39.4 ± 4.8 to 41.4 ± 4.0 mL/kg/min ($P < 0.001$, ES 0.45). A second study [11] of 57 female high school basketball players reported a mean improvement from 34.6 ± 4.5 to 39.5 ± 5.7 mL/kg/min ($P < 0.0001$, ES 0.43). A third investigation [12] of female high school soccer players found a mean improvement from 37.9 ± 4.5 to 410.1 ± 4.7 mL/kg/min ($P < 0.0001$, ES 0.23).

Critical Points

- Vertical jump height: mixed results
- Single-leg hop: distance hopped consistently improved
- Sprint tests: mixed results
- Agility tests: consistently improved
- Estimated VO_2max: improved after Sportsmetrics training

Conclusions

Few ACL intervention training programs have undergone rigorous investigation regarding their effectiveness in reducing injury rates, improving potentially deleterious lower limb kinematic and kinetic factors, and enhancing athletic performance indicators. Only three programs significantly reduced the incidence of noncontact ACL injuries (Sportsmetrics, PEP, and KIPP). At the time of writing, only one investigation on the effectiveness of KIPP program (on reducing landing impact forces) had been published; no other analyses of this program in terms of kinematic or kinetic factors were available. The PEP program, studied in four investigations [15, 19, 21, 22], showed little effect in improving the knee valgus moment, knee valgus angle, vertical jump height, sprint time, and agility. However, this program did result in increased knee flexion and hip abduction, decreased hip internal rotation, and improvements in the strength of the quadriceps and hamstrings. The Sportsmetrics program has been analyzed in several investigations, both within the authors' center [2–4, 6–12, 16] and at independent institutions [5, 13–15, 17]. The majority of studies have shown improvements in lower limb alignment, hamstrings strength, hamstrings to quadriceps ratio, vertical jump height, single-leg hop test distances, speed, and estimated maximal aerobic capacity. Future investigations should prospectively determine adequate sample size using power analyses, report ES in addition to P values, and analyze unplanned, reactive tests in laboratory studies.

References

1. Ettlinger CF, Johnson RJ, Shealy JE (1995) A method to help reduce the risk of serious knee sprains incurred in alpine skiing. Am J Sports Med 23(5):531–537
2. Hewett TE, Stroupe AL, Nance TA, Noyes FR (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24(6):765–773
3. Barber-Westin SD, Hermeto A, Noyes FR (2015) A six-week neuromuscular and performance training program improves speed, agility, dynamic balance, and core endurance in junior tennis players. J Athl Enhancement 4(1). https://doi.org/10.4172/2324-9080.1000185
4. Barber-Westin SD, Smith ST, Campbell T, Noyes FR (2010) The drop-jump video screening test: retention of improvement in neuromuscular control in female volleyball players. J Strength Cond Res 24(11):3055–3062. https://doi.org/10.1519/JSC.0b013e3181d83516
5. Chimera NJ, Swanik KA, Swanik CB, Straub SJ (2004) Effects of plyometric training on muscle-activation strategies and performance in female athletes. J Athl Train 39(1):24–31
6. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27(6):699–706
7. Noyes FR, Barber-Westin SD (2014) Neuromuscular retraining intervention programs: do they reduce noncontact anterior cruciate ligament injury rates in adolescent female athletes? Arthroscopy 30(2):245–255. https://doi.org/10.1016/j.arthro.2013.10.009
8. Noyes FR, Barber-Westin SD (2015) Neuromuscular retraining in female adolescent athletes: effect on athletic performance indices and noncontact anterior cruciate ligament injury rates. Sports 3:56–76. https://doi.org/10.3390/sports3020056

9. Noyes FR, Barber-Westin SD, Fleckenstein C, Walsh C, West J (2005) The drop-jump screening test: difference in lower limb control by gender and effect of neuromuscular training in female athletes. Am J Sports Med 33(2):197–207
10. Noyes FR, Barber-Westin SD, Smith ST, Campbell T (2011) A training program to improve neuromuscular indices in female high school volleyball players. J Strength Cond Res 25(8):2151–2160. https://doi.org/10.1519/JSC.0b013e3181f906ef
11. Noyes FR, Barber-Westin SD, Smith ST, Campbell T, Garrison TT (2012) A training program to improve neuromuscular and performance indices in female high school basketball players. J Strength Cond Res 26(3):709–719. https://doi.org/10.1519/JSC.0b013e318228194c
12. Noyes FR, Barber-Westin SD, Tutalo Smith ST, Campbell T (2013) A training program to improve neuromuscular and performance indices in female high school soccer players. J Strength Cond Res 27(2):340–351. https://doi.org/10.1519/JSC.0b013e31825423d9
13. Pfile KR, Gribble PA, Buskirk GE, Meserth SM, Pietrosimone BG (2016) Sustained improvements in dynamic balance and landing mechanics after a 6-week neuromuscular training program in college women's basketball players. J Sport Rehabil 25(3):233–240. https://doi.org/10.1123/jsr.2014-0323
14. Tsang KK, Dipasquale AA (2011) Improving the q:h strength ratio in women using plyometric exercises. J Strength Cond Res 25(10):2740–2745. https://doi.org/10.1519/JSC.0b013e31820d9e95
15. Vescovi JD, Canavan PK, Hasson S (2008) Effects of a plyometric program on vertical landing force and jumping performance in college women. Phys Ther Sport 9(4):185–192. https://doi.org/10.1016/j.ptsp.2008.08.001
16. Waxman JP, Walsh MS, Smith ST, Berg WP, Ward RM, Noyes FR (2016) The effects of a 6-week neuromuscular training program on quadriceps and hamstring muscle activation during side-cutting in high school female athletes. Athlet Train Spts Health Care 8(4):164–176. https://doi.org/10.3928/19425864-20160303-03
17. Wilkerson GB, Colston MA, Short NI, Neal KL, Hoewischer PE, Pixley JJ (2004) Neuromuscular changes in female collegiate athletes resulting from a plyometric jump-training program. J Athl Train 39(1):17–23
18. Gilchrist J, Mandelbaum BR, Melancon H, Ryan GW, Silvers HJ, Griffin LY, Watanabe DS, Dick RW, Dvorak J (2008) A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med 36(8):1476–1483. https://doi.org/10.1177/0363546508318188
19. Lim BO, Lee YS, Kim JG, An KO, Yoo J, Kwon YH (2009) Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. Am J Sports Med 37(9):1728–1734. https://doi.org/10.1177/0363546509334220
20. Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, Garrett W Jr (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33(7):1003–1010. https://doi.org/10.1177/0363546504272261
21. Pollard CD, Sigward SM, Ota S, Langford K, Powers CM (2006) The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. Clin J Sport Med 16(3):223–227
22. Rodriguez C, Echegoyen S, Aoyama T (2017) The effects of "Prevent Injury and Enhance Performance Program" in a female soccer team. J Sports Med Phys Fitness. https://doi.org/10.23736/S0022-4707.17.07024-4
23. Vescovi JD, VanHeest JL (2010) Effects of an anterior cruciate ligament injury prevention program on performance in adolescent female soccer players. Scand J Med Sci Sports 20(3):394–402. https://doi.org/10.1111/j.1600-0838.2009.00963.x
24. Irmischer BS, Harris C, Pfeiffer RP, DeBeliso MA, Adams KJ, Shea KG (2004) Effects of a knee ligament injury prevention exercise program on impact forces in women. J Strength Cond Res 18(4):703–707
25. Pfeiffer RP, Shea KG, Roberts D, Grandstrand S, Bond L (2006) Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. J Bone Joint Surg Am 88(8):1769–1774
26. Steffen K, Myklebust G, Olsen OE, Holme I, Bahr R (2008) Preventing injuries in female youth football--a cluster-randomized controlled trial. Scand J Med Sci Sports 18(5):605–614. https://doi.org/10.1111/j.1600-0838.2007.00703.x
27. Soligard T, Myklebust G, Steffen K, Holme I, Silvers H, Bizzini M, Junge A, Dvorak J, Bahr R, Andersen TE (2008) Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ 337:a2469
28. Steffen K, Emery CA, Romiti M, Kang J, Bizzini M, Dvorak J, Finch CF, Meeuwisse WH (2013) High adherence to a neuromuscular injury prevention programme (FIFA 11+) improves functional balance and reduces injury risk in Canadian youth female football players: a cluster randomised trial. Br J Sports Med 47(12):794–802. https://doi.org/10.1136/bjsports-2012-091886
29. Holm I, Fosdahl MA, Friis A, Risberg MA, Myklebust G, Steen H (2004) Effect of neuromuscular training on proprioception, balance, muscle strength, and lower limb function in female team handball players. Clin J Sport Med 14(2):88–94
30. Myklebust G, Engebretsen L, Braekken IH, Skjolberg A, Olsen OE, Bahr R (2003) Prevention of anterior cruciate ligament injuries in female team

handball players: a prospective intervention study over three seasons. Clin J Sport Med 13(2):71–78

31. Petersen W, Braun C, Bock W, Schmidt K, Weimann A, Drescher W, Eiling E, Stange R, Fuchs T, Hedderich J, Zantop T (2005) A controlled prospective case control study of a prevention training program in female team handball players: the German experience. Arch Orthop Trauma Surg 125(9):614–621
32. Pasanen K, Parkkari J, Pasanen M, Hiilloskorpi H, Makinen T, Jarvinen M, Kannus P (2008) Neuromuscular training and the risk of leg injuries in female floorball players: cluster randomised controlled study. BMJ 337:a295
33. Pasanen K, Parkkari J, Pasanen M, Kannus P (2009) Effect of a neuromuscular warm-up programme on muscle power, balance, speed and agility: a randomised controlled study. Br J Sports Med 43(13):1073–1078. https://doi.org/10.1136/bjsm.2009.061747
34. Labella CR, Huxford MR, Grissom J, Kim KY, Peng J, Christoffel KK (2011) Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. Arch Pediatr Adolesc Med 165(11):1033–1040. https://doi.org/10.1001/archpediatrics.2011.168
35. Kiani A, Hellquist E, Ahlqvist K, Gedeborg R, Michaelsson K, Byberg L (2010) Prevention of soccer-related knee injuries in teenaged girls. Arch Intern Med 170(1):43–49. https://doi.org/10.1001/archinternmed.2009.289
36. Hagglund M, Atroshi I, Wagner P, Walden M (2013) Superior compliance with a neuromuscular training programme is associated with fewer ACL injuries and fewer acute knee injuries in female adolescent football players: secondary analysis of an RCT. Br J Sports Med 47(15):974–979. https://doi.org/10.1136/bjsports-2013-092644
37. Lindblom H, Walden M, Carlfjord S, Hagglund M (2014) Implementation of a neuromuscular training programme in female adolescent football: 3-year follow-up study after a randomised controlled trial. Br J Sports Med 48(19):1425–1430. https://doi.org/10.1136/bjsports-2013-093298
38. Lindblom H, Walden M, Hagglund M (2012) No effect on performance tests from a neuromuscular warm-up programme in youth female football: a randomised controlled trial. Knee Surg Sports Traumatol Arthrosc 20(10):2116–2123. https://doi.org/10.1007/s00167-011-1846-9
39. Walden M, Atroshi I, Magnusson H, Wagner P, Hagglund M (2012) Prevention of acute knee injuries in adolescent female football players: cluster randomised controlled trial. BMJ 344:e3042. https://doi.org/10.1136/bmj.e3042
40. Filipa A, Byrnes R, Paterno MV, Myer GD, Hewett TE (2010) Neuromuscular training improves performance on the star excursion balance test in young female athletes. J Orthop Sports Phys Ther 40(9):551–558. https://doi.org/10.2519/jospt.2010.3325
41. Klugman MF, Brent JL, Myer GD, Ford KR, Hewett TE (2011) Does an in-season only neuromuscular training protocol reduce deficits quantified by the tuck jump assessment? Clin Sports Med 30(4):825–840. https://doi.org/10.1016/j.csm.2011.07.001
42. Myer GD, Ford KR, Brent JL, Hewett TE (2006) The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. J Strength Cond Res 20(2):345–353. https://doi.org/10.1519/R-17955.1
43. Myer GD, Ford KR, Brent JL, Hewett TE (2007) Differential neuromuscular training effects on ACL injury risk factors in “high-risk” versus “low-risk” athletes. BMC Musculoskelet Disord 8:39. https://doi.org/10.1186/1471-2474-8-39
44. Myer GD, Ford KR, McLean SG, Hewett TE (2006) The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. Am J Sports Med 34(3):445–455
45. Myer GD, Ford KR, Palumbo JP, Hewett TE (2005) Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. J Strength Cond Res 19(1):51–60
46. Myer GD, Stroube BW, DiCesare CA, Brent JL, Ford KR, Heidt RS Jr, Hewett TE (2013) Augmented feedback supports skill transfer and reduces high-risk injury landing mechanics: a double-blind, randomized controlled laboratory study. Am J Sports Med 41(3):669–677. https://doi.org/10.1177/0363546512472977
47. Paterno MV, Myer GD, Ford KR, Hewett TE (2004) Neuromuscular training improves single-limb stability in young female athletes. J Orthop Sports Phys Ther 34(6):305–316
48. Lephart SM, Abt JP, Ferris CM, Sell TC, Nagai T, Myers JB, Irrgang JJ (2005) Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. Br J Sports Med 39(12):932–938. https://doi.org/10.1136/bjsm.2005.019083
49. Chappell JD, Limpisvasti O (2008) Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. Am J Sports Med 36(6):1081–1086. https://doi.org/10.1177/0363546508314425
50. Herman DC, Onate JA, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, Padua DA (2009) The effects of feedback with and without strength training on lower extremity biomechanics. Am J Sports Med 37(7):1301–1308. https://doi.org/10.1177/0363546509332253
51. Herman DC, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, Padua DA (2008) The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. Am J Sports Med 36(4):733–740. https://doi.org/10.1177/0363546507311602

52. Zebis MK, Andersen LL, Brandt M, Myklebust G, Bencke J, Lauridsen HB, Bandholm T, Thorborg K, Holmich P, Aagaard P (2016) Effects of evidence-based prevention training on neuromuscular and biomechanical risk factors for ACL injury in adolescent female athletes: a randomised controlled trial. Br J Sports Med 50(9):552–557. https://doi.org/10.1136/bjsports-2015-094776
53. Zebis MK, Bencke J, Andersen LL, Dossing S, Alkjaer T, Magnusson SP, Kjaer M, Aagaard P (2008) The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. Clin J Sport Med 18(4):329–337. https://doi.org/10.1097/JSM.0b013e31817f3e35
54. Herrington L (2010) The effects of 4 weeks of jump training on landing knee valgus and crossover hop performance in female basketball players. J Strength Cond Res 24(14):3427–3432. https://doi.org/10.1519/JSC.0b013e3181c1fcd8
55. DiStefano LJ, Padua DA, DiStefano MJ, Marshall SW (2009) Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. Am J Sports Med 37(3):495–505. https://doi.org/10.1177/0363546508327542
56. Baldon Rde M, Moreira Lobato DF, Yoshimatsu AP, dos Santos AF, Francisco AL, Pereira Santiago PR, Serrao FV (2014) Effect of plyometric training on lower limb biomechanics in females. Clin J Sport Med 24(1):44–50. https://doi.org/10.1097/01.jsm.0000432852.00391.de
57. Baldon Rde M, Lobato DF, Carvalho LP, Wun PY, Santiago PR, Serrao FV (2012) Effect of functional stabilization training on lower limb biomechanics in women. Med Sci Sports Exerc 44(1):135–145. https://doi.org/10.1249/MSS.0b013e31822a51bb
58. Hurd WJ, Chmielewski TL, Snyder-Mackler L (2006) Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. Knee Surg Sports Traumatol Arthrosc 14(1):60–69
59. Kato S, Urabe Y, Kawamura K (2008) Alignment control exercise changes lower extremity movement during stop movements in female basketball players. Knee 15(4):299–304. https://doi.org/10.1016/j.knee.2008.04.003
60. McLeod TC, Armstrong T, Miller M, Sauers JL (2009) Balance improvements in female high school basketball players after a 6-week neuromuscular-training program. J Sport Rehabil 18(4):465–481
61. Wilderman DR, Ross SE, Padua DA (2009) Thigh muscle activity, knee motion, and impact force during side-step pivoting in agility-trained female basketball players. J Athl Train 44(1):14–25
62. Nagano Y, Ida H, Akai M, Fukubayashi T (2011) Effects of jump and balance training on knee kinematics and electromyography of female basketball athletes during a single limb drop landing: pre-post intervention study. Sports Med Arthrosc Rehabil Ther Technol 3(1):14. https://doi.org/10.1186/1758-2555-3-14
63. Pfile KR, Hart JM, Herman DC, Hertel J, Kerrigan DC, Ingersoll CD (2013) Different exercise training interventions and drop-landing biomechanics in high school female athletes. J Athl Train 48(4):450–462. https://doi.org/10.4085/1062-6050-48.4.06
64. Steib S, Zahn P, Zu Eulenburg C, Pfeifer K, Zech A (2016) Time-dependent postural control adaptations following a neuromuscular warm-up in female handball players: a randomized controlled trial. BMC Sports Sci Med Rehabil 8:33. https://doi.org/10.1186/s13102-016-0058-5
65. Weltin E, Gollhofer A, Mornieux G (2017) Effects of perturbation or plyometric training on core control and knee joint loading in women during lateral movements. Scand J Med Sci Sports 27(3):299–308. https://doi.org/10.1111/sms.12657
66. Hopper A, Haff EE, Barley OR, Joyce C, Lloyd RS, Haff GG (2017) Neuromuscular training improves movement competency and physical performance measures in 11-13-year-old female netball athletes. J Strength Cond Res 31(5):1165–1176. https://doi.org/10.1519/JSC.0000000000001794
67. Letafatkar A, Rajabi R, Tekamejani EE, Minoonejad H (2015) Effects of perturbation training on knee flexion angle and quadriceps to hamstring cocontraction of female athletes with quadriceps dominance deficit: pre-post intervention study. Knee 22(3):230–236. https://doi.org/10.1016/j.knee.2015.02.001
68. Ericksen HM, Thomas AC, Gribble PA, Armstrong C, Rice M, Pietrosimone B (2016) Jump-landing biomechanics following a 4-week real-time feedback intervention and retention. Clin Biomech (Bristol, Avon) 32:85–91. https://doi.org/10.1016/j.clinbiomech.2016.01.005
69. Brown TN, Palmieri-Smith RM, McLean SG (2014) Comparative adaptations of lower limb biomechanics during unilateral and bilateral landings after different neuromuscular-based ACL injury prevention protocols. J Strength Cond Res 28(10):2859–2871. https://doi.org/10.1519/JSC.0000000000000472
70. Stearns KM, Powers CM (2014) Improvements in hip muscle performance result in increased use of the hip extensors and abductors during a landing task. Am J Sports Med 42(3):602–609. https://doi.org/10.1177/0363546513518410
71. Bell DR, Oates DC, Clark MA, Padua DA (2013) Two- and 3-dimensional knee valgus are reduced after an exercise intervention in young adults with demonstrable valgus during squatting. J Athl Train 48(4):442–449. https://doi.org/10.4085/1062-6050-48.3.16
72. Celebrini RG, Eng JJ, Miller WC, Ekegren CL, Johnston JD, MacIntyre DL (2012) The effect of a novel movement strategy in decreasing ACL risk factors in female adolescent soccer players. J Strength Cond Res 26(12):3406–3417. https://doi.org/10.1519/JSC.0b013e3182472fef

73. Greska EK, Cortes N, Van Lunen BL, Onate JA (2012) A feedback inclusive neuromuscular training program alters frontal plane kinematics. J Strength Cond Res 26(6):1609–1619. https://doi.org/10.1519/JSC.0b013e318234ebfb
74. Otsuki R, Kuramochi R, Fukubayashi T (2014) Effect of injury prevention training on knee mechanics in female adolescents during puberty. Int J Sports Phys Ther 9(2):149–156
75. Padua DA, Distefano LJ, Marshall SW, Beutler AI, de la Motte SJ, Distefano MJ (2012) Retention of movement pattern changes after a lower extremity injury prevention program is affected by program duration. Am J Sports Med 40(2):300–306. https://doi.org/10.1177/0363546511425474
76. Barber-Westin SD, Hermeto AA, Noyes FR (2010) A six-week neuromuscular training program for competitive junior tennis players. J Strength Cond Res 24(9):2372–2382. https://doi.org/10.1519/JSC.0b013e3181e8a47f
77. Steffen K, Bakka HM, Myklebust G, Bahr R (2008) Performance aspects of an injury prevention program: a ten-week intervention in adolescent female football players. Scand J Med Sci Sports 18(5):596–604. https://doi.org/10.1111/j.1600-0838.2007.00708.x
78. Donnell-Fink LA, Klara K, Collins JE, Yang HY, Goczalk MG, Katz JN, Losina E (2015) Effectiveness of knee injury and anterior cruciate ligament tear prevention programs: a meta-analysis. PLoS One 10(12):e0144063. https://doi.org/10.1371/journal.pone.0144063
79. Gagnier JJ, Morgenstern H, Chess L (2013) Interventions designed to prevent anterior cruciate ligament injuries in adolescents and adults: a systematic review and meta-analysis. Am J Sports Med 41(8):1952–1962. https://doi.org/10.1177/0363546512458227
80. Myer GD, Sugimoto D, Thomas S, Hewett TE (2013) The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. Am J Sports Med 41(1):203–215. https://doi.org/10.1177/0363546512460637
81. Sadoghi P, von Keudell A, Vavken P (2012) Effectiveness of anterior cruciate ligament injury prevention training programs. J Bone Joint Surg Am 94(9):769–776. https://doi.org/10.2106/JBJS.K.00467
82. Sugimoto D, Myer GD, Barber Foss KD, Pepin MJ, Micheli LJ, Hewett TE (2016) Critical components of neuromuscular training to reduce ACL injury risk in female athletes: meta-regression analysis. Br J Sports Med. https://doi.org/10.1136/bjsports-2015-095596
83. Sugimoto D, Myer GD, McKeon JM, Hewett TE (2012) Evaluation of the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a critical review of relative risk reduction and numbers-needed-to-treat analyses. Br J Sports Med 46(14):979–988. https://doi.org/10.1136/bjsports-2011-090895
84. Taylor JB, Waxman JP, Richter SJ, Shultz SJ (2015) Evaluation of the effectiveness of anterior cruciate ligament injury prevention programme training components: a systematic review and meta-analysis. Br J Sports Med 49(2):79–87. https://doi.org/10.1136/bjsports-2013-092358
85. Grimm NL, Shea KG, Leaver RW, Aoki SK, Carey JL (2013) Efficacy and degree of bias in knee injury prevention studies: a systematic review of RCTs. Clin Orthop Relat Res 471(1):308–316. https://doi.org/10.1007/s11999-012-2565-3
86. Noyes FR, Barber Westin SD (2012) Anterior cruciate ligament injury prevention training in female athletes: a systematic review of injury reduction and results of athletic performance tests. Sports Health 4(1):36–46. https://doi.org/10.1177/1941738111430203
87. Stevenson JH, Beattie CS, Schwartz JB, Busconi BD (2015) Assessing the effectiveness of neuromuscular training programs in reducing the incidence of anterior cruciate ligament injuries in female athletes: a systematic review. Am J Sports Med 43(2):482–490. https://doi.org/10.1177/0363546514523388
88. Fritz CO, Morris PE, Richler JJ (2012) Effect size estimates: current use, calculations, and interpretation. J Exp Psychol Gen 141(1):2–18. https://doi.org/10.1037/a0024338
89. Heidt RS Jr, Sweeterman LM, Carlonas RL, Traub JA, Tekulve FX (2000) Avoidance of soccer injuries with preseason conditioning. Am J Sports Med 28(5):659–662
90. Murray JJ, Renier CM, Ahern JJ, Elliott BA (2016) Neuromuscular training availability and efficacy in preventing anterior cruciate ligament injury in high school sports: a retrospective cohort study. Clin J Sport Med. https://doi.org/10.1097/JSM.0000000000000398
91. Soderman K, Werner S, Pietila T, Engstrom B, Alfredson H (2000) Balance board training: prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. Knee Surg Sports Traumatol Arthrosc 8(6):356–363
92. Wedderkopp N, Kaltoft M, Lundgaard B, Rosendahl M, Froberg K (1999) Prevention of injuries in young female players in European team handball. A prospective intervention study. Scand J Med Sci Sports 9(1):41–47
93. Arnason A, Engebretsen L, Bahr R (2005) No effect of a video-based awareness program on the rate of soccer injuries. Am J Sports Med 33(1):77–84
94. Junge A, Rosch D, Peterson L, Graf-Baumann T, Dvorak J (2002) Prevention of soccer injuries: a prospective intervention study in youth amateur players. Am J Sports Med 30(5):652–659
95. Campbell CJ, Carson JD, Diaconescu ED, Celebrini R, Rizzardo MR, Godbout V, Fletcher JA, McCormack R, Outerbridge R, Taylor T, Constantini N, Cote M, Canadian Academy of Sport and Exercise Medicine (2014) Canadian Academy of Sport and

Exercise Medicine position statement: neuromuscular training programs can decrease anterior cruciate ligament injuries in youth soccer players. Clin J Sport Med 24(3):263–267. https://doi.org/10.1097/JSM.0000000000000068

96. Labella CR, Hennrikus W, Hewett TE, Council on Sports Medicine and Fitness, and Section on Orthopaedics (2014) Anterior cruciate ligament injuries: diagnosis, treatment, and prevention. Pediatrics. https://doi.org/10.1542/peds.2014-0623
97. Shultz SJ, Schmitz RJ, Benjaminse A, Collins M, Ford K, Kulas AS (2015) ACL research retreat VII: an update on anterior cruciate ligament injury risk factor identification, screening, and prevention. J Athl Train 50(10):1076–1093. https://doi.org/10.4085/1062-6050-50.10.06
98. Renstrom P, Ljungqvist A, Arendt E, Beynnon B, Fukubayashi T, Garrett W, Georgoulis T, Hewett TE, Johnson R, Krosshaug T, Mandelbaum B, Micheli L, Myklebust G, Roos E, Roos H, Schamasch P, Shultz S, Werner S, Wojtys E, Engebretsen L (2008) Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. Br J Sports Med 42(6):394–412. https://doi.org/10.1136/bjsm.2008.048934
99. Wojtys EM, Huston LJ, Taylor PD, Bastian SD (1996) Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. Am J Sports Med 24(2):187–192
100. Ramsbottom R, Brewer J, Williams C (1988) A progressive shuttle run test to estimate maximal oxygen uptake. Br J Sports Med 22(4):141–144
101. Caraffa A, Cerulli G, Projetti M, Aisa G, Rizzo A (1996) Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. Knee Surg Sports Traumatol Arthrosc 4(1):19–21