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Anterior Cruciate Ligament Injuries in Female Athletes

Part 2, A Meta-analysis of Neuromuscular Interventions Aimed at Injury Prevention

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Female athletes have a 4 to 6 times higher incidence of anterior cruciate ligament injury than do male athletes participating in the same landing and pivoting sports. This greater risk of anterior cruciate ligament injury, coupled with a geometric increase in participation (doubling each decade), has led to a significant rise in anterior cruciate ligament injuries in female athletes. The gender gap in anterior cruciate ligament injury, combined with evidence that the underpinnings of this serious health problem are neuromuscular in nature, leads to the development of neuromuscular interventions designed to prevent injury. A systematic review of the published literature yielded 6 published interventions targeted toward anterior cruciate ligament injury prevention in female athletes. Four of 6 significantly reduced knee injury incidence, and 3 of 6 significantly reduced anterior cruciate ligament injury incidence in female athletes. A meta-analysis of these 6 studies demonstrates a significant effect of neuromuscular training programs on anterior cruciate ligament injury incidence in female athletes (test for overall effect, $Z = 4.31$, $P < .0001$). Examination of the similarities and differences between the training regimens gives insight into the development of more effective and efficient interventions. The purpose of this "Current Concepts" review is to highlight the relative effectiveness of these interventions in reducing anterior cruciate ligament injury rates and to evaluate the common training components between the training studies. In addition, the level of rigor of these interventions, the costs and the difficulty of implementation, the compliance with these interventions, and the performance benefits are discussed. This review summarizes conclusions based on evidence from the common components of the various interventions to discuss their potential to reduce anterior cruciate ligament injury risk and assess their potential for combined use in more effective and efficient intervention protocols.

Keywords: neuromuscular training; balance training; strength training; plyometrics; knee injury; anterior cruciate ligament (ACL) injury; injury prevention; gender differences

Anterior cruciate ligament research has resulted in more than 2000 scientific articles published outlining injury incidence, mechanism, surgical repair techniques, and rehabilitation of this important stabilizing knee ligament.[10] However, despite the many scientific advances in the treatment of ACL injury, osteoarthritis occurs at a 10 times greater rate in ACL-injured patients, regardless of the treatment (nonsurgical management vs surgical treatment).[8] Epidemiologic research has demonstrated that female athletes have a 4- to 6-fold increased risk of ACL injury compared with their male counterparts playing at similar levels in the same sports.[1,30,34] The increased ACL injury risk coupled with increased sports participation by young women over the past 30 years (9-fold increase in high school[37] and 5-fold increase in collegiate sports[36]) have increased public awareness and fueled many gender-specific mechanistic and interventional investigations. This significant problem is associated with a large health care cost, in the range of $625 million annually, in addition to increased potential for loss of entire seasons of sports participation, loss of possible scholarship funding, lowered academic performance, long-term disability, and up to 100 times greater risk of radiographically diagnosed osteoarthritis.[5,9,11]

Efforts to prevent ACL injury in female athletes should focus on the factors that make women more susceptible to injury and to develop interventions to aid in the prevention of these injuries. The following meta-analysis attempts to quantitatively combine the results of 6 independent studies

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TABLE 1
Estimation of Injury Incidence per 1000 Exposures

Study	Sport	Age, y	Group	Exposure: Game and Practice	ACL Knee Injuries, incidence/1000 exposures	Noncontact ACL, incidence/1000 exposures
Hewett et al[17]	Basketball, soccer, volleyball	14-18	Trained (n = 366)	17 222	0.12[a]	0.00[a]
			Untrained (n = 463)	23 138	0.22[a]	0.22[a]
Heidt et al[15]	Soccer	14-18	Trained (n = 42)	3948[b]	0.25	
			Untrained (n = 258)	24 252[b]	0.33	
Soderman et al[43]	Soccer	20.4 ± 4.6	Trained (n = 62)	4123[c]	0.73	
		20.5 ± 5.4	Untrained (n = 78)	4631[c]	0.22	
Myklebust et al[34]	Team handball	16-35	Trained (n = 263)[d]	38 085[c]	0.08	
			Untrained (n = 645)[d]	55 318[c]	0.25	
			Trained (n = 850)[e]	93 403[c]	0.18	0.08[a]
			Untrained (n = 942)[f]	104 468[c]	0.28	0.17[a]
Mandelbaum et al[31]	Soccer	14-18	Trained (n = 1885)	67 860		0.09[a]
			Untrained (n = 3818)	137 448		0.49[a]
Petersen et al[40]	Team handball	Adult	Untrained (n = 134)	—[c]	0.08	
			Untrained (n = 142)	—[c]	0.42	

[a]Significant decrease in injuries through training intervention.
[b]Injury exposures estimated from Hewett et al[17] soccer exposures times 2 seasons.
[c]Injury exposures estimated as 2 hours = 1 practice or game exposure.
[d]Screening year 2000-2001, completed intervention versus dropped out.
[e]Screening year 2000-2001, intervention, all athletes.
[f]Screening year 1998-1999, no intervention.

drawn from a systematic review of the published literature regarding ACL injury interventions in female athletes. This analysis summarizes and synthesizes the findings of all 6 studies to draw generalized conclusions on the effectiveness of neuromuscular training interventions in reducing ACL injuries during sports competition in female athletes.

METHODS

This meta-analysis was designed to identify the effectiveness of training interventions to prevent ACL injuries during athletics. We searched electronic databases, Medline (1966-2004) and CINAHL (1982-2004), with the subject terms *knee injury* and *sports injury*.[44] The results were further limited to the terms *intervention* and *control*. Articles were included in the meta-analysis if they were a randomized controlled trial (RCT) or prospective cohort study and investigated a neuromuscular training intervention used for prevention of ACL injury in female athletes. Abstracts were excluded from this review. Six articles were identified that met the systematic review criteria (Table 1). The total number of ACL injuries in the training and control groups was entered into a statistical package to calculate the overall effect of training.[4] The analysis used weighted sample sizes for each study.

RESULTS

The results of the meta-analysis are outlined in Figure 1. The meta-analysis shows the total ACL injuries in the training group (n = 29) versus the control group (n = 110). These 6 studies significantly favor injury prevention training programs for reducing ACL injuries (test for overall effect, Z = 4.31, $P < .0001$). A power analysis yielded a required minimum number of 344 athletes in both the trained and untrained groups for 80% power in the reviewed studies. The 6 studies are described in the following section by order of publication date.

The Effects of Intervention Training on ACL Injury Incidence

Hewett et al. Hewett et al[17] (Table 2) conducted a prospective cohort study monitoring high school–aged female soccer, basketball, and volleyball players; 15 female teams (n = 366) were included in the neuromuscular training intervention, and an additional 15 female teams (n = 463) were used as a control group. Thirteen male teams (n = 434) were also included as an additional control group. A limitation of this study was that there were more volleyball players in the trained group than

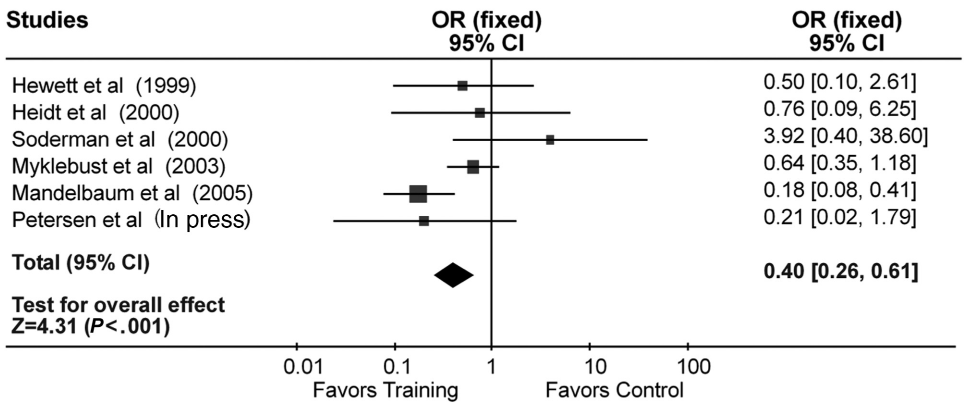

Figure 1. Effect of injury prevention training programs on the odds of an ACL injury occurring. Total ACL injuries in the training group (n = 29) versus the control group (n = 110). Meta-analysis favors injury prevention training on ACL injury outcome. OR, odds ratio; CI, confidence interval.

in the untrained group. The intervention consisted of a 6-week neuromuscular training intervention[19] performed 3 times a week (60-90 min/session) before their competitive season.

Noncontact ACL injury risk was significantly reduced in the trained female athletes ($P \leq .05$). The rate of noncontact ACL injury was decreased 72% in those athletes who underwent preseason neuromuscular training compared with the untrained group. Five untrained female athletes (3 basketball, 2 soccer) sustained a noncontact ACL injury compared with none of the trained female athletes ($P \leq .05$). This was the first study to demonstrate the effects of neuromuscular training on reducing ACL injury rates in female athletes. It is a well-designed prospective study but would be stronger as an RCT.

Heidt et al. Heidt et al[15] performed a neuromuscular training intervention on high school female soccer players (Table 1). The study consisted of a control group (n = 258) and an intervention group (n = 42) trained before the start of their competitive seasons. The intervention group participated in 13 treadmill speed-training sessions (2 times/wk) and 7 foot agility sessions (line jumps that progress from unidirectional to multidirectional to 2-in incremented barrier hops) completed within a 7-week period.

The trained group had significantly fewer (14%) overall injuries than did the control group (33.7%, $P < .01$). However, there were no differences in the occurrence of ACL injuries between the groups. Anterior cruciate ligament rupture occurred in 2.4% of the trained group compared with 3.1% of the controls. The occurrence of medial collateral ligament sprain/tear was 2.4% compared with 2.3% in the intervention and control groups, respectively.

The lack of significant difference in ACL injury rates may possibly be attributed to the fact that only minimal low-intensity plyometrics were incorporated into the training protocol (footwork and agility drills). In addition, the study was underpowered (the N was too low) to demonstrate differences in ACL injury rates. Furthermore, the definitions of injuries were vague and nonobjective (eg, bursitis was defined as a knee injury in this study).

Soderman et al. A randomized control trial on professional female soccer players from Sweden was conducted by Soderman et al[43] (Table 1). Seven teams (n = 62) were randomized into the intervention group, and 6 teams (n = 78) served as controls. There were no significant differences in traumatic injuries or ACL injuries between groups. The intervention group had 4.45 injuries per 1000 hours of practices and games compared to 3.83 in the control group. The intervention group sustained significantly more major injuries, 8 major injuries, than did the controls (1 major injury, $P = .02$).

This study was conducted with a very low number of subjects and inappropriate statistical power. The treatment did not appear to be effective in reducing ACL injury incidence. The lack of significant difference in ACL injury rates may possibly be attributed to the fact that only minimal balance training was incorporated into the protocol. Furthermore, the injury reporting mechanisms were poorly described. In addition, the balance board training was performed by the athlete at home. This training approach may have poor compliance. The balance training program performed 3 times per week did not reduce lower extremity sprains.

Myklebust et al. Myklebust et al[34] performed an ACL intervention study in female team handball players. This prospective cohort study monitored ACL injury incidence for 3 consecutive seasons in 3 divisions of Norwegian female handball. An intervention designed to prevent ACL injuries was instituted during the second (58 teams, n = 855) and third seasons (52 teams, n = 850) of play. There were 29 ACL injuries in the initial control season compared with 23 and 17 in the next 2 intervention seasons, respectively ($P = .62$ and .15, respectively). There was a significant reduction in the number of noncontact injuries from the control season to the second intervention year (18 control year, 7 intervention year 2; $P = .04$). When separated by division and training intervention compliance, the elite division that performed the intervention had a significant reduction in ACL injuries (2.3%) compared with the athletes who did not complete the intervention (8.9%, $P = .01$). When normalized to injury

TABLE 2
Details on Compliance of the 6 Intervention Programs

Study	Compliance, %	Compliance Criteria, % training sessions	Session Training Time, min	Total Sessions	Total Training Time, h/athlete	Trainer	Labor Costs,[a] $	Equipment	Estimated Equipment Costs,[b] $	Estimated Total Costs,[c] $
Hewett et al[17]	70	66 (4/6 weeks)	75	18 preseason (3 per week for 6 weeks)	22.5	1 ATC/team (15 teams)	14.11	Universal Strength Olympic Gym ($4000); gymnastics mats ($500); videos ($10) (15 teams)	129.60	143.70
Heidt et al[15]	100	Not provided	60	20 preseason (3 times/wk in 7 weeks)	20	Trainer	0	Fee for service	375.00	375.00
Soderman et al[43]	70	32 (35/108 sessions)	12.5	108 in season (30 in first month; 3 times/wk for 26 weeks)	22.5	Self	0	89 balance boards ($50/board)	50.00	50.00
Myklebust et al[34]	26 (first intervention year)	71 (15/21 preseason sessions)	15	62: 21 preseason (3 times/wk for 7 weeks) and 41 in season (1 time/wk for 41 weeks)	15.5	Teammate	0	12 balance boards and mats ($50.00 each); videos ($10.00) (59 teams)	42.10	42.10
	29 (second intervention year)	71 (15/21 preseason sessions)	15	62: 21 preseason (3 times/wk for 7 weeks) and 41 in season (1 time/wk for 41 weeks)	15.5	1 PT/team (44 teams)	23.10	12 balance boards and mats ($50.00 each); videos ($10.00) (48 teams)	34.40	57.50
Mandelbaum et al[31]	98	Returned questionnaire[d]	20	36 in season (assumes that the warm-up was performed for all exposures—games and practices)	12	Coach	0	Video ($10.00)	0.50	0.50
Petersen et al[40]	83	Team completed the training program and participated in handball season	10	65: 24 preseason (3 times/wk for 8 weeks); assumes 41 in-season weeks (1 time/wk)	10.8	Coach or PT	23.20	12 balance boards and mats ($50.00 each) (10 teams)	4.50	27.70

[a]Per athlete per season. Based on $28.80/h for physical therapist (PT) salary and $15.30/h for certified athletic trainer (ATC) salary (national averages from the American Physical Therapy Association and the National Athletic Trainers' Association).
[b]Per athlete per season or per team if equipment was not given to every individual. Prices estimated and standardized between studies.
[c]Per athlete per season.
[d]The coach was given the questionnaire on the last week of the season and was asked to observe if the athletes on the team performed the prescribed protocol. If the questionnaire was returned, then all athletes on the team were considered compliant.

exposures (player-hours), ACL injury risk decreased 36%. In the elite division among those who met the compliance criteria (at least 15 training sessions of 15-21 possible sessions), there was a significant drop in injury rates ($P = .01$). Half of the ACL injuries were noncontact injuries. When the authors separated out the contact injuries, they observed 18 noncontact ACL injuries in the control season and 7 in the second intervention season ($P = .04$).

Although there was a trend toward a reduction in ACL injuries for the entire cohort ($P = .15$), it was not statistically significant except for the elite division ($P = .06$). One explanation for this phenomenon is the fact that the elite players participated in 5 to 10 practice sessions per week (in contrast to the minimum 15 sessions) over the 5- to 7-week training period. Therefore, the Division I athletes may have had more training opportunities to gain ACL injury prevention protective effects through training.

Mandelbaum et al. This controlled cohort study[31] enrolled soccer players between the ages of 14 and 18 years over a 2-year period. During the first year, 52 teams (n = 1041) were enrolled in the intervention group, and 95 age- and skill-matched teams (n = 1905) that were untrained served as controls. The second-year intervention group consisted of 45 teams (n = 844), and 112 teams (n = 1913) served as the control group.

During the first season, there were 2 noncontact ACL injuries resulting from 37 476 athlete exposures in the intervention group (0.05 incidences per 1000 exposures), which was significantly fewer ($P < .001$) than the injuries of the control group—32 ACL injuries resulting from 68 580 athlete exposures (0.47 incidences per 1000 exposures). Similar results were found in the second year, with 0.13 and 0.51 incidences per 1000 exposures in the intervention and control groups, respectively ($P < .01$). Combined over the 2 years of the study, a total of 6 ACL ruptures occurred in the training group in comparison with 67 in the control group.

This was a prospective study that would be stronger as a randomized control trial. Furthermore, the mechanism of injury to differentiate contact from noncontact injuries was not clearly defined. This study employed end-of-season injury reporting, which can be problematic. The ACL injuries may have been underreported in this setting. In addition, the mechanism (contact vs noncontact) may have potential inaccuracies.

Petersen et al. Petersen et al[40] performed a controlled, prospective case control study of ACL injury prevention in German female team handball players. An intervention designed to prevent ACL injuries was instituted with 10 teams, with a total of 134 players, 10 other teams (142 players) followed their normal training routines. The ACL injury prevention intervention was based primarily on the work of Myklebust et al[34] and consisted of 3 exercise components: balance board exercises, jump exercises, and balance mat exercises. Each component was progressed in 6 phases from easy to more difficult.

There were 5 ACL injuries in the control group compared with 1 in the trained group (odds ratio, 0.17; 95% confidence interval, 0.02-1.5). There was not a significant reduction in the number of ACL injuries in the intervention compared with the control group, although ACL injury risk was 80% lower in the intervention group.

Although the findings of the study were not statistically significant, the results looked potentially promising. A problem with this study was that it was underpowered; the number of subjects was likely too low to accept the null hypothesis of no difference. Our power analysis predicted that 134 players in the intervention group and 142 players in the control group would not give sufficient power to detect differences between groups. However, in this case, the treatment did not appear to be effective in bringing about the desirable change (ACL injury reduction).

DISCUSSION

Common Components of the Effective Interventions

The effects of 3 of the 6 interventions that reduced ACL injury rates appear to be relatively similar, arising from a common rationale derived from performance enhancement training and physical rehabilitation for athletes.[15,17,31,34,40,43] A comprehensive review of all 6 interventions reviewed suggests that multiple neuromuscular training components may provide some level of ACL injury risk reduction. Neuromuscular training likely alters active knee joint stabilization and appears to aid in decreasing ACL injury rates in female athletes.

An examination of the data extracted from the intervention studies leads one to a few potentially valuable generalizations. Plyometric training combined with biomechanical analysis and technique training were common components of all 3 studies that effectively reduced ACL injury rates. Balance training alone is probably not as effective for injury prevention as when it is combined with other types of training. One needs to consider whether the teams' or athletes' primary goal is injury prevention, performance enhancement, or both. In-season training alone is probably the most cost-effective and efficient method for achieving beneficial injury prevention effects, although the lack of high-intensity overload in these programs likely precludes measurable performance enhancement effects. Recent studies employing the in-season training program of Mandelbaum et al[31] demonstrated that the ACL injury reduction is not observed until later in the season in collegiate soccer, and this in-season program did not appear to change biomechanical risk factors.[12,41] Finally, the most effective and efficient programs appear to require a combination of components, and the effects of these components are potentially additive.

Plyometric Component of the Effective Interventions. The studies by Hewett et al,[17] Myklebust et al,[34] Mandelbaum et al,[31] and Petersen et al[40] incorporated high-intensity jumping plyometric movements that progressed beyond footwork and agility into their intervention designs. The studies by Heidt et al[15] and Soderman et al[43] did not. All 4 studies that incorporated plyometrics reduced ACL risk, whereas the 2 studies that did not incorporate plyometrics did not reduce ACL injury risk. The plyometric component of an exercise intervention, which trains the muscles, connective tissue, and nervous system to effectively carry out the stretch-shortening cycle and focuses on proper technique and body mechanics, appears to reduce serious ligamentous injuries, specifically ACL injuries. Training interventions that incorporate plyometrics with safe levels of varus or valgus stress may induce more muscle-dominant neuromuscular adaptations to correct for neuromuscular imbalances in female athletes.[18,28] Such adaptations may better prepare an athlete for more multidirectional sport activities and may reduce positioning that puts high loads on the ACL.[27]

Biomechanics Technique Feedback Effects. The 3 programs that significantly reduced ACL injury risk also used analysis of the movement biomechanics and feedback to the athlete regarding proper body position and technique. The studies by Hewett et al,[17] Myklebust et al[34] and Mandelbaum et al[31] all incorporated critical technique analysis and feedback during training into their intervention designs. The studies by Heidt et al[15] and Soderman et al[43] did not. Of these 2 studies, neither reduced ACL injury risk. Education and enforced awareness of dangerous positions and mechanisms of ACL injury have also been shown to decrease ACL injuries.[21] Ski instructors viewed videotapes of ACL injuries and were encouraged to formulate their own preventive strategies. Anterior cruciate ligament injuries were decreased by more than 50% with this technique. Olsen et al[38] reported that a video-based injury awareness program did not decrease injury rates in soccer. Awareness programs alone without training may not be effective in landing and cutting sports. However, elements from this ski study may be applicable to other sports. It is important to teach athletes to avoid biomechanically disadvantageous and dangerous positions in any sport. Griffin[13] identified 3 potentially dangerous maneuvers in basketball that she proposed should be modified through training to prevent ACL injury. She suggested that athletes land in a more bent knee position and decelerate before a cutting maneuver. Preliminary work implementing the different techniques on a small sample of athletes showed a trend toward a decrease in injury rates between the trained versus untrained study groups.[13]

Hewett et al[17] expanded this concept and used a trainer to provide feedback and awareness to an athlete during training. Verbalization and visualizations such as "on your toes," "straight as an arrow," "light as a feather," "shock absorber," and "recoil like a spring" were used by the trainer as verbal and visualization cues for each phase of the jump. Athletes were required to perform jumps using only proper technique. As the athletes became fatigued, they were required to stop if they could not execute each jump with correct biomechanics. Myklebust et al[34] used partner training to provide the critical feedback. Partners encouraged each other to focus on the quality of their movements, specifically on the knee-over-the-toe position. Mandelbaum et al[31] used a training video to emphasize proper body position and movement mechanics during running and landing. Three studies[17,31,34] specifically cited critical analysis and feedback as contributors to the reduction of ACL injuries in their respective studies.

Balance and Core Stability Training. Balance training alone may not be sufficient to produce significant ACL injury prevention effects. Soderman et al[43] focused on balance training, primarily using unstable wobble boards. However, the intervention in this study was not effective in reducing ACL injuries. Caraffa et al[3] prospectively evaluated the effect of balance board exercises on noncontact ACL injury rates in male soccer players. Soderman et al[43] attempted to replicate the Caraffa et al[3] study performed in male athletes with female athletes, although the impressive effect on ACL injury was not replicated in the female soccer players. The training consisted of approximately 20 minutes of balance board exercises divided into 5 phases. They compared athletes who participated in proprioceptive training before their competitive seasons versus controls and found a significantly decreased rate of ACL injuries in the trained group.[3]

The studies by Hewett et al[17] and Mandelbaum et al[31] incorporated single-leg core stability (functional balance) training, primarily using hold positions from a decelerated landing, into their intervention designs. Myklebust et al[34] examined the effects of a relatively comprehensive functional balance training intervention. Their intervention elaborated on the balance board protocol of Caraffa et al[3] by adding a focus to improve awareness and knee control during standing, cutting, jumping, and landing. They demonstrated a reduction in the incidence of ACL injury in women's elite handball division over 2 competitive seasons.[34] Others have shown that this type of proprioceptive and balance training can improve postural control and that lack of postural control and stability was also related to increased risk of ankle injury.[20,39,45,46] Likewise, improvement in single-leg stability can be gained with a neuromuscular training intervention that incorporates perturbations into balance training on unstable surfaces.[39] Balance training has also been shown to improve maximum lower extremity strength and decrease side-to-side imbalances in stabilometric measures.[16] Side-to-side imbalances in lower extremity measures have been shown to be a risk factor for ACL injury.[22] The above findings support the integration of proprioceptive stability and balance training in ACL injury interventions. However, it appears that balance drills using unstable platforms alone may not be sufficient to reduce ACL injury risk.

Strength Training. The studies by Hewett et al[17] and Mandelbaum et al[31] incorporated strength training in their intervention protocols. Myklebust et al,[34] Heidt et al,[15] Soderman et al,[43] and Petersen et al[40] did not include strength training in their interventions. The designs that incorporated strength training were among the most effective at decreasing ACL injury rates, but strength training may not be a prerequisite for prevention, as the Myklebust et al[34] study was effective and it did not incorporate strength training. Strength training may be optional for injury prevention; however, the biomechanical and strength changes observed may have been owing in part to the strength training component.[19] Resistance training alone has not been shown to reduce ACL injuries. However, there is inferential evidence that resistance training may reduce injury based on the beneficial adaptations that occur in bones, ligaments, and tendons after training.[7,23] Lehnhard et al[26] were able to significantly reduce injury rates with the addition of a strength training regimen to a men's soccer team. They monitored injuries for 2 years without training and 2 years with the strength training treatment added. Although they did not observe a reduction specifically in ACL injuries, they did report a decrease in percentage of injuries that were ligament sprains. The significant reduction of ligament sprains may have been related to reduced knee injury (43%) reported in the second year of posttrained competition.[26] Resistance training may aid in the reduction of ACL injuries when combined with other training components; however, the efficacy of a single-faceted resistance training protocol on ACL injury prevention has yet to be determined.

Efficacy and Efficiency of These Interventions

Relative Difficulty, Intensity, and Time Cost. The relative difficulty, cost, and efficiency of these interventions need to be addressed. The details of each program are shown in Table 2. The relative training volume and intensity could be ranked as follows: Hewett et al[17] > Heidt et al[15] >> Myklebust et al[34] = Petersen et al[40] > Mandelbaum et al[31] >> Soderman et al.[43] The studies by Hewett et al,[17] Heidt et al,[15] Mandelbaum et al[31] and Myklebust et al[34] incorporated more high-intensity movements into their intervention designs. The Hewett et al[17] and Heidt et al[15] study involved preseason high-intensity neuromuscular training, Myklebust et al[34] and Petersen et al[40] involved both preseason and in-season medium-intensity (prepractice warm-up) training, Mandelbaum et al[31] involved in-season medium-intensity (prepractice warm-up) training, and Soderman et al[43] involved in-season low-intensity balance board neuromuscular training. The training time per athlete is initially high for the preseason programs, but this time per athlete tends to balance out over the length of the season. These programs also save time during the season. However, a combination preseason and in-season program, similar to that of Myklebust et al,[34] may prove the most efficacious.

Compliance. Reported compliance rates and definition of compliance vary greatly between studies (Table 2). Hewett et al[17] reported 70% compliance rates, Soderman et al[43] reported 63%, Heidt et al[15] reported 100%, Mandelbaum et al[31] reported 98%, and Myklebust et al[34] reported rates as low as 28%. Petersen et al[40] did not report compliance rates. Myklebust et al[34] examined compliance with the greatest rigor and in the greatest detail, which may account for their relatively low percentage compliance. They separated their data by training intervention compliance. In the elite division among those who met the compliance criteria (at least 15 training sessions of 15-21 possible sessions), there was a significant drop in injury rates. Myklebust et al[34] should be commended for their more detailed analysis of compliance, which was not well addressed in the other studies. They also had the most stringent inclusion criteria. Their data demonstrate what a challenge compliance is, even with athletes of high caliber, as only 26% of the teams were judged compliant the first year and 29% the second year of intervention. Table 2 indicates that when compliance is an important consideration, the team coaches are likely to direct the most compliant programs, and they are the most inexpensive source of training assistance.

Relative Performance-Enhancement Effects of the Interventions

The high-intensity neuromuscular overload associated with strength training and plyometrics likely enhances both muscular power and performance and the injury prevention effects of neuromuscular training. Strength training may be optional for injury prevention; however, this type of training is prerequisite to overloading the muscle and gaining optimal performance-enhancement effects. Overload is required for measurable muscular adaptation. Hewett et al[17] and Mandelbaum et al[31] both incorporated a strength training component into their interventions. The difficulty in assessing the relative effects on performance is that only one study has assessed effects on performance.[19] These authors demonstrated an approximately 10% increase in vertical jump height with 6 weeks of training. However, numerous neuromuscular training programs designed for young women can be effective at improving performance measures of speed, strength, and power.[19,24,25,32] Female athletes may especially benefit from neuromuscular training, as they often display decreased baseline levels of strength and power compared with their male counterparts.[19,29] Dynamic neuromuscular training has also been demonstrated to reduce gender-related differences in force absorption, active joint stabilization, muscle imbalances, and functional biomechanics while increasing strength of structural tissues (bones, ligaments, and tendons).[6,7,19,32,33,42]

Neuromuscular training may reduce the risk of injury in female athletes; however, without the performance-enhancement effects, athletes may not be motivated to participate in a neuromuscular training program. Prevention training that is oriented toward reducing ACL injuries in female athletes may have compliance rates as low as 28%.[34] However, training for performance enhancement can have better compliance ranging from 80% to 90%.[2,14,23,24,47] Hence, if protocols are designed for both performance enhancement and ACL injury prevention techniques, neuromuscular training may be instituted on a widespread basis with potentially higher athlete compliance.

Limitations of These Intervention Studies

There are several limitations to this body of studies as a whole and to each of the 6 individual studies. The number of participants in each study is low for epidemiologic studies. Therefore, the number of both injuries and exposures is relatively low, and statistically, these studies are underpowered. In addition, the measure of exposures was not consistent. Four of these studies are not randomized controlled trails. Randomized controlled trials are needed to better discern the effects of these interventions. There was no mention made of a power analysis in these studies.

Teams in the Hewett et al[17] study were not cluster randomized, and compliance was not rigorously assessed. The Soderman et al[43] and Petersen et al[40] studies were underpowered to attempt to examine ACL injury epidemiology. Soderman et al[43] had only 62 trained and 78 untrained athletes, and Petersen et al[40] had only 137 and 142 athletes in their intervention and control groups, respectively. The training protocol was not well documented in the Soderman et al[43] study. Compliance was also not well documented by either of these studies.

The Heidt et al[15] study also had low numbers for attempting to examine injury epidemiology. The lack of a randomized design was also a distinct weakness. The lack of significant difference in ACL injury rates in the Heidt et al[15] study may possibly be attributed to the fact that only minimal low-intensity plyometrics were incorporated into the training protocol (footwork and agility drills). Furthermore, the injury reporting methods and the injury definitions were poorly described. In addition, although the study was purported to be randomized in the methods, it was not an RCT. Subjects volunteered to either participate in the training or not (personal communication from author).

The Myklebust et al[34] study was a well-done prospective study. However, there were methodological limitations to this study. They include a lack of sufficient documentation of ACL injury status. In addition, the authors make several references to nonsignificant results without performing a power analysis for the study. A power analysis should have been performed to determine if the lack of significance was likely owing to an insufficient number of subjects. This inaction is a potential weakness of all the reported studies. The Mandelbaum et al[31] study also had poor compliance reporting. Exposures were not closely surveyed, as the reported numbers appear to be gross estimates of exposure. In addition, the incidence of injury in the untrained athletes was high for that age group compared to other values reported in the literature.

Limitations of the Meta-analysis

There are several limitations to our meta-analysis of the literature. One potential limitation is publication bias. Only positive findings tend to get published in the literature. This factor could potentially bias our analysis toward positive results. An important potential limitation of this analysis is general heterogeneity between studies. Another potential problem, which is a subset of the previous limitation, is the mixed designs between studies. It may not be appropriate to compare studies with different study designs. Yet another potential limitation of this analysis related to study heterogeneity in the different treatments. It is not clear whether one should expect the same effect from the 5 different treatments we analyzed. However, each of the authors did hypothesize that the intervention would reduce ACL injury. Finally, there is the problem of different follow-up times in the various investigations, implying that the odds ratio is potentially not the best statistic to meta-analyze. However, it would be very difficult to calculate relative risks (adjusted to follow-up times and expressed in person-years), so all that can be done is to list these problems as limitations of the analysis.

CONCLUSION AND FUTURE DIRECTIONS

There is evidence that neuromuscular training decreases potential biomechanical risk factors for ACL injury and decreases ACL injury incidence in female athletes. Three of the 6 interventions in this meta-analysis demonstrated significant effects on ACL injury rates.

Five of 6 demonstrated positive trends and reduction in odds ratios. However, we do not yet know which of these components is most effective or whether their effects are combinatorial. Future directions will be to assess the relative efficacy of these interventions alone and in combination to achieve the optimal effect in the most efficient manner possible. Final conclusions from this examination of these 6 studies are that neuromuscular training may assist in the reduction of ACL injuries in females athletes if

1. plyometrics, balance, and strengthening exercises are incorporated into a comprehensive training protocol;
2. the training sessions are performed more than 1 time per week; and
3. the duration of the training program is a minimum of 6 weeks in length.

The studies by Hewett et al,[17] Myklebust et al[34] and Mandelbaum et al[31] incorporated high-intensity plyometric movements that progressed beyond footwork and agility in the intervention. The studies by Heidt et al[15] and Soderman et al[43] did not. All 3 studies that incorporated high-intensity plyometrics reduced ACL risk, whereas the studies that did not incorporate high-intensity plyometrics did not reduce ACL injury risk. The plyometric component of these interventions, which trains the muscles, connective tissue, and nervous system to effectively carry out the stretch-shortening cycle and that focuses on proper technique and body mechanics, appears to reduce ACL injuries.

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