Sports **2015**, *3*, 56-76; doi:10.3390/sports3020056

OPEN ACCESS

sports

ISSN 2075-4663

www.mdpi.com/journal/sports

Article

Neuromuscular Retraining in Female Adolescent Athletes: Effect on Athletic Performance Indices and Noncontact Anterior Cruciate Ligament Injury Rates

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Academic Editor: Eling Douwe de Bruin

Received: 25 March 2015 / Accepted: 11 May 2015 / Published: 13 May 2015

Abstract: While many anterior cruciate ligament (ACL) prevention programs have been published, few have achieved significant reductions in injury rates and improvements in athletic performance indices; both of which may increase compliance and motivation of athletes to participate. A supervised neuromuscular retraining program (18 sessions) was developed, aimed at achieving both of these objectives. The changes in neuromuscular indices were measured after training in 1000 female athletes aged 13–18 years, and the noncontact ACL injury rate in 700 of these trained athletes was compared with that of 1120 control athletes. There were significant improvements in the drop-jump test, ($p < 0.0001$, effect size [ES] 0.97), the single-leg triple crossover hop ($p < 0.0001$, ES 0.47), the *t*-test ($p < 0.0001$, ES 0.64), the multi-stage fitness test ($p < 0.0001$, ES 0.57), hamstring strength ($p < 0.0001$), and quadriceps strength ($p < 0.01$). The trained athletes had a significant reduction in the noncontact ACL injury incidence rate compared with the controls (1 ACL injury in 36,724 athlete-exposures [0.03] and 13 ACL injuries in 61,244 exposures [0.21], respectively, $p = 0.03$). The neuromuscular retraining program was effective in reducing noncontact ACL injury rate and improving athletic performance indicators.

Keywords: anterior cruciate ligament; neuromuscular retraining; noncontact ACL injury; female athlete

1. Introduction

It is well known that adolescent female athletes have a 4- to 8-fold higher incidence of sustaining a complete noncontact anterior cruciate ligament (ACL) injury compared with male athletes participating in the same sport or activity [1–3]. A complete ACL injury is indicated by 5 mm or more of increased anteroposterior tibial displacement on an instrumented or clinical Lachman test and a fully positive pivot shift test (grade 2 or 3 on a 0–3 point scale). At least two-thirds of ACL tears are noncontact in nature and occur when an athlete is cutting, pivoting, accelerating, decelerating, or landing from a jump [4–6]. The short- and long-term consequences of ACL injuries in young athletes include high cost of medical treatment, a heightened risk of future reinjuries (to both knee joints), psychological morbidity, lost productivity in work or school, potential for lost scholarship funding, and premature osteoarthritis [7–10]. Over the past 20 years, many ACL injury prevention programs have been developed in an effort to decrease the injury rate in female athletes [11,12]. There is tremendous variation among these programs in regard to the components that comprise the intervention, the duration and intensity of training, supervision and compliance tracking, and when training takes place (pre-season or within-season). Consensus statements from research retreats and committees agree that the ideal ACL-injury prevention program remains unclear in terms of exercise components, amount of supervision required, and timing due to the complex problem of the injury itself [13–16]. Reviews of published programs have suggested that plyometric and strengthening components are important components, and that the favorable effects of training are most pronounced in female soccer players under 18 years of age [17–21].

Investigators from the sixth ACL Research Retreat recommended that ACL injury prevention programs should be evaluated to determine their effect on both noncontact ACL injuries and athletic performance indices [15]. It has been hypothesized that programs that have a positive influence on both injury rate reduction and performance enhancement will have better compliance with training [15]. This is due to the perception that convincing athletes, parents, coaches, and others of the necessity for injury prevention training may be more successful if evidence exists that athletic performance will also benefit. Although several programs have reported ACL injury incidence data, few have undergone a rigorous assessment of their ability to improve athletic performance indices.

A 6-week, 18-session supervised ACL injury prevention program was developed and first described in 1996 [22]. Subsequently, this program was shown to significantly reduce the incidence of noncontact ACL injuries in young female athletes [23]. A group of 366 athletes that completed training had 17,222 athlete-exposures (AE) and 0 noncontact ACL injuries. A control group of 463 athletes that did not undergo training had 23,138 AE and five noncontact ACL injuries (incidence rate, 0.022, $p < 0.05$). Studies in relatively small numbers of athletes that completed this training program (34 volleyball players [24], 57 basketball players [25], 62 soccer players [26]), demonstrated significant improvements in athletic indices such as estimated VO_2max [24–26], agility and sprint tests [26], a sit-up test [24], and vertical jump tests [24,26]. There were also improvements in overall lower limb alignment on landing during a video drop-jump in these athletes [24–26]. As our experience continued to grow with this training program, we wished to determine if these same goals (significant decrease in ACL injury rates and increase in athletic performance indices) would be met in a larger group of athletes.

The goal of this investigation was to determine, in a group of 1000 female adolescent athletes, if significant improvements occurred after training in tests that measured neuromuscular and athletic indices such as lower limb alignment on a drop-jump, distance and limb symmetry on single-leg hop tests, agility, speed, lower limb muscle strength, and estimated VO_2max. The second goal was to determine noncontact ACL injury rates in a subset of 700 of the trained athletes compared with 1120 control athletes matched for age, sport, and body mass index. We hypothesized that this program would significantly improve neuromuscular and athletic performance indicators and significantly decrease the risk of noncontact ACL injuries in female high school athletes.

2. Subjects and Methods

2.1. Subjects

There were 1,000 female athletes (age 13–18 years, height 167 ± 7 cm, weight 59 ± 9 kg, body mass index 21 ± 3) from Cincinnati area high schools and club leagues who volunteered to participate in the training program over an 8-year time period. Initially, researchers and athletic trainers from our Center approached coaches and invited their teams to participate (free of charge) [23]. After the first four years, individual athletes began to request to participate based on observations and discussions with others who had completed team training. All athletes in this study completed one 6-week training session; those who completed more than one session were excluded. From these 1000 athletes, a subgroup of 700 were followed for one season to determine ACL injury incidence rates. These 700 athletes completed training just before the beginning of their sports season and were in high schools in which our athletic trainers worked and were able to track athlete-exposures (AE) on a weekly basis during the subsequent sports season. One AE equaled participation in one practice or game.

Before data collection, all athletes and their parents provided their informed written consent in accordance with the Internal Review Board of the Jewish Hospital of Cincinnati, Ohio for use of human subjects. All procedures were performed in accordance with the 1964 World Medical Association Declaration of Helsinki.

The sports the trained athletes participated in at the time of the study were volleyball (401), basketball (202), soccer (192), lacrosse (30), softball (15), field hockey (8), gymnastics (7), track and field (4), and multiple sports (141). Tanner staging [27,28] was not performed on these subjects. There were 118 subjects aged 13, 353 subjects aged 14, 260 subjects aged 15, 174 subjects aged 16, 83 subjects aged 17, and 12 subjects aged 18. In girls, the mean time to achieve peak height velocity is 11.5 years [29] and the mean time to reach skeletal maturity is 13.3 years [30]. Therefore, it appeared that the majority of athletes had completed expected growth and maturation. No athlete had a history of a serious knee injury or surgery.

An additional 1120 athletes from Cincinnati area high school teams served as controls and were matched to the trained athletes for age (13–18 yr), sport, and body mass index (21 ± 3). These athletes participated in their team practices and games, but did not perform any component of the ACL injury prevention program. Because this was not a randomized study, there was no intention to treat analysis performed.

Exclusionary criteria for training for this investigation were pre-existing multiple ankle sprains, evidence of a lower extremity joint effusion, or a history of a noteworthy knee injury such as a ligament rupture, meniscus tear, or patellar dislocation.

2.2. Study Design

The athletes underwent a series of tests no more than one week before the first training session (pre-test) and no more than one week after the last training session (post-test) in either the laboratory or at the training sites, which were usually indoor high school gymnasiums or soccer fields. Before testing and training, the athletes completed approximately 10 min of supervised dynamic warm-up exercises. Training sessions lasted 1–1.5 h and were held three days a week (Monday, Wednesday, Friday) in the afternoons for six weeks. All 18 training sessions were supervised by certified Sportsmetrics instructors. The entire program was completed just before the athletes' sports season began (*i.e.*, pre-season). Because neuromuscular and athletic performance testing evolved over time, with the addition and deletion of certain tests, not all subjects underwent the same tests reported. In addition, certain agility and speed tests were designated for specific sports and, therefore, were not conducted in all athletes. The number of athletes that completed each test is shown in Table 1.

Table 1. Number of athletes that completed each test.

Test	Number of Athletes
Video drop-jump	912
Single-leg triple crossover hop	280
Single-leg triple hop	223
Vertical jump, no countermovement	807
Vertical jump with countermovement	502
Agility *t*-test	221
37-m sprint	136
18-m sprint	350
Multi-stage fitness test	356
Sit-up test	110
Isokinetic strength test, 300°/s, quadriceps & hamstrings	141

Athlete exposures (AE) were documented for every practice and game the players (trained and control) participated in on a weekly basis. Coaches, athletic trainers, and research assistants assisted with ensuring weekly AE logs were completed. There was a larger number of control athletes than trained athletes due to the voluntary nature of this multi-year study; more athletes declined training than accepted to participate.

All knee injuries were tracked for the one sport season that followed the training. All athletes that sustained knee injuries were examined by the senior author. ACL ruptures were determined clinically according to grade 2–3 Lachman [31] and pivot shift [32] tests and magnetic resonance imaging.

2.3. Video Drop-Jump Test

A video drop-jump test was used to measure overall lower limb alignment in the coronal plane [33]. A camcorder equipped with a memory stick was placed on a stand 102.24 cm in height and positioned approximately 365.76 cm in front of a box (dimensions: 30.48 cm in height, 38.1 cm in width). Velcro circles (2.54 cm) were placed on each of the four corners of the box that faced the camera. The athletes were dressed in fitted, dark shorts and low cut gym shoes. Reflective markers were placed at the greater trochanter and lateral malleolus of both legs and velcro circles were positioned on the center of each patella. The jump-land sequence was demonstrated and the athletes completed two practice trials allowed to ensure they understood the test. No verbal instructions regarding how to land or jump were provided. The athletes were simply instructed to land straight in front of the box to be in the correct angle for the camera to record properly. The athletes performed the jump-land sequence by first jumping off the box, landing, and immediately performing a maximum vertical jump. This sequence was repeated three times.

After completion of the test, all three trials were viewed and the one that best represented each athlete's jumping ability was selected for measurement. Advancing the video frame-by-frame, the following images were captured as still photographs: (1) pre-land, the frame in which the athlete's toes just touched the ground after the jump off of the box; (2) land, the frame in which the athlete was at the deepest point; and (3) take-off, the frame that demonstrated the initial forward and upward movement of the arms and the body as the athlete prepared to go into the maximum vertical jump.

The captured images were imported into a hard drive of a computer and digitized on the screen using commercially available software (Cincinnati Sportsmedicine Research and Education Foundation, Cincinnati, OH). A calibration procedure was done by placing the cursor and clicking in the center of each Velcro marker on each of the four corners of the drop jump box. The anatomic reference points represented by the reflective markers were selected by clicking in a designated sequence the cursor for each image.

The absolute cm of separation distance between the right and left hip and normalized separation distances for the knees and ankles, standardized according to the hip separation distance, were produced using the software. Normalized knee separation distance was calculated as knee separation distance/hip separation distance × 100 and normalized ankle separation distance was calculated as ankle separation distance/hip separation distance × 100. We empirically believe that < 60% knee separation distance represents a distinctly abnormal lower limb valgus alignment position.

The reliability of the drop-jump video test was previously documented [33]. Test-retest trials produced high intraclass correlation coefficients (ICC) for the hip separation distance (pre-land, 0.96; land, 0.94; take-off, 0.94). For the within-test trial, the ICCs for the hip, knee, and ankle separation distance were all ≥0.90. We previously found no correlation between knee and ankle separation distances [33] and, therefore, report only absolute and normalized knee separation distances in this investigation.

2.4. Single-Leg Hop Tests

The first 57 athletes tested completed one single-leg hop test (triple) [34]. Then, because no limb symmetry problems were detected, we added a second hop (triple crossover [34]) in order to potentially detect limb asymmetry in more athletes. A tape measure was secured to the ground for a distance of approximately 6 m. Testing was first performed on either the right or leg, which was selected at random. The athletes stood on the leg to be tested with their toe just behind the starting line. For the triple hop test, three consecutive hops were done going straight ahead on the leg. In the triple crossover hop test, three consecutive hops were done on one leg, crossing diagonally over the measuring tape on each hop. The athletes had to be in control and hold the landing of the third hop for 3 s for the test to be valid. The athletes were allowed to use their arms for balance as required. Two or three practice trials were done for each test on each leg. Then, two hops were done on each limb. For athletes who completed both hops, the triple hop was done first on each leg, followed by the triple crossover hop. The right-left leg limb symmetry index was calculated by dividing the maximum distance hopped (best result) of the right leg by the maximum distance hopped (best result) of the left leg, and then multiplying the result by 100. These tests have excellent reliability, with ICC > 0.85 [35,36].

2.5. Vertical Jump Tests

The athletes' vertical jump was determined using the Vertec Jump Training System (Sports Imports, Columbus, OH). First, the standing reach was measured with the athlete standing with the heels touching the ground. Then, a maximum jump without arm swing or a countermovement maximum jump with arm swing was performed three times and the highest jump obtained recorded. In the first 305 athletes tested, only the maximum jump without arm swing test was performed. In the next 502 athletes, both tests were performed. The ICC using the Vertec is excellent (>0.90 [37,38]).

2.6. Agility t-Test

The *t*-test is a commonly used measure of agility [39–43]. The athletes sprinted from a standing point in a straight line to a cone placed 9-m away. Then, the athletes side-shuffled to their left without crossing their feet to another cone placed 4.5-m away. After touching this cone, they side-shuffled to their right to a third cone placed 9-m away, side-shuffled back to the middle cone, and then ran backwards to the starting position. Two tests were completed, with the best time recorded. The time to complete this test was recorded with a digital stopwatch in one-hundredths of a second. This test has excellent reliability, with ICCs ≥ 0.90 [44,45].

2.7. Sprint Tests

The athletes performed a single maximum sprint, starting from a stationary position with one foot in front of the other. Encouragement was provided throughout the run. The tests were performed (of either 18-m or 37-m in length) with the time recorded to the nearest one hundredth of a second with a digital stopwatch. During the first two years of this study, the 38-m sprint was conducted, followed for the remaining years of the study with the 18-m sprint in accordance with discussions with coaches who wanted to determine sprint speed over the shorter distance. The reliability of sprint tests using a hand-held stopwatch is excellent, with ICCs > 0.90 [46].

2.8. Multi-Stage Fitness Test

A common field test used to estimate maximal oxygen uptake (VO_2max) is the 20-meter multi-stage fitness test (MSFT).[47] The equipment required are the MSFT commercially available audio compact disc (CD) and a CD player. Two cones were used to mark the course. The athletes began with their toes behind the designated starting cone. The second cone was located 20 m away. On command, the athletes ran back and forth between the two cones in time to recorded beeps on the CD. The athletes performed shuttle runs back and forth along the 20-m course, keeping in time with the series of signals (beeps) on the CD by touching the appropriate end cone in time with each audio signal. The frequency of the audible signals was progressively increased until the athletes reached volitional exhaustion and could no longer maintain pace with the audio signals, indicated when three beeps were missed in a row. The level and number of shuttles reached before the athletes were unable to keep up with the audio recording were recorded. The VO_2max of each athlete was estimated using the equation described by Ramsbottom *et al.* [48]: VO_2max = (5.857 × speed on the last stage)—19.458. The test-retest reliability of this test is excellent, with ICCs > 0.90 [49,50].

2.9. Sit-up Test

The athletes were placed supine, with the knees bent and feet flat on the floor (held in place by a partner) and arms folded across the chest. On command, full sit-ups were performed by raising up so that the elbows touched the knees and then lowering back down to the floor. The number of repetitions completed in 60 s was recorded. The sit-up test has been reported to have acceptable reliability in normal subjects of 0.84 (ICC) [51].

2.10. Isokinetic Strength Test

Isokinetic knee flexion and extension testing was performed at 300 deg/s (Biodex Medical Systems, Inc., Shirley, NY, USA) [52–56]. The athletes were positioned in the device with appropriate torso, pelvis and thigh straps placed according to the manufacturer's protocol. The pivot point of the arm of the dynamometer was aligned with the lateral epicondyle of the knee, with the knee flexed to 90°. The chair was adjusted for each athlete to allow proper positioning. The range of motion during the test was fixed from 90° to 0°. Gravitational factors were calculated by the dynamometer and automatically compensated for during the tests. The athletes were familiarized with the machine and the test velocity by performing three to four sub-maximal trials. There was a 30-s rest period between the flexion and extension tests. Verbal encouragement was given throughout the tests, as the athletes were told to kick as hard and as fast as possible, but no visual feedback was available. A total of 10 repetitions were completed and the highest peak torque value used for analyses. Mean peak torque values (Nm) were normalized for body-weight (BW) in kg, and were expressed therefore as a ratio (Nm/BW). Acceptable reliability of isokinetic measurements in children and adults have been reported by many investigators [52–56].

2.11. Neuromuscular Retraining Program

The neuromuscular retraining program (Sportsmetrics) has been described in detail elsewhere [11,24–26]. The dynamic warm-up (Table 2), jump/plyometric (Table 3), and flexibility components were the same for all athletes. The philosophy regarding the jump/plyometric component of the program was to emphasis and teach correct jumping and landing techniques. Specific drills and instruction were used to train the athletes to preposition their entire body safely when accelerating into a jump and when decelerating on landing. The exercises progressed from simple jumping drills (to instill correct form) to multi-directional, single-foot hops and plyometrics with an emphasis on quick turnover (to add movements that mimic sports-specific motions such as cutting, pivoting, and change of direction). The jump training was divided into three two-week phases, each of which had a different training focus and exercises. Sports-specific agility, reaction, speed, endurance, and strength drills and exercises were incorporated for approximately 30–45 min for basketball, soccer, volleyball, and lacrosse players. All sessions ended with static stretching of the hamstrings, iliotibial band, quadriceps, hip flexors, gastrocnemius, soleus, deltoid, triceps, biceps, and low back.

Table 2. Dynamic warm-up*.

Exercise	Instructions
Toe walk	Walk on the toes and keep the legs straight. Do not allow the heel to touch the ground.
Heel walk	Walk on the heels and keep the legs straight. Do not allow the toes to touch the ground. Do not lock the knees, but keep them slightly flexed.
Straight leg march	Walk with both legs straight, alternating lifting up each leg as high as possible without compromising form. Keep the knees straight and the posture erect. Do not the lean backward.
Leg cradle	Walk forward and keep the entire body straight and neutrally aligned. Lift one leg off of the ground in front of the body, bending at the knee. Turn the knee outward and grasp the foot with both hands. Hold this position for 3 s, then place the foot back down and repeat with the opposite leg.
Hip rotator walk	Pretend there is an obstacle directly in front of you. Face forward and keep the shoulders and hips square. Extend one leg at the hip and keep the knee bent. Rotate the leg out at the hip and bend the knee to 90°. Rotate and bring the leg up and over the obstacle, then place it back on the ground. Repeat with the opposite leg.
High knee skip	This exercise involves skipping in which one knee is driven up in the air as high as possible, while the other is used to land and hop off the ground. Immediate repeat the skip on the opposite side with each land. Swing the arm opposite of the high knee up in the air to help gain height.
High knees	This exercise involves jogging where, with each step, the knees are driven up as high as possible using short, choppy steps. The shoulders and hips are kept square throughout the exercise.
Glut kicks	This exercise involves jogging where, with each step, the athlete kicks the feet back as if trying to reach the gluts with the heel, using short, choppy steps. The shoulders and hips are kept square throughout the exercise.
Stride out	Begin jogging forward using an exaggerated running form. Drive the knees as high as possible and kick the feet back, as if trying to make a large complete circle with the legs. Stay up on the balls of the feet throughout the exercise.
All-out sprint	Sprint forward as fast as possible, making sure to maintain proper technique and running form.

* The exercises are performed across the width of a court or field, or for approximately 20–30 s. This component will take approximately 10 min to complete.

Table 3. Jump training component.

Jumps	**Duration**	
Phase I: Technique	Week 1	Week 2
Wall jump	20 s	25 s
Tuck jump	20 s	25 s
Squat jump	10 s	15 s
Barrier jump (side-to-side)	20 s	25 s
Barrier jump (forward-back)	20 s	25 s
180° jump	20 s	25 s
Broad jump (hold 5 s)	5 reps	10 reps
Bounding in place	20 s	25 s
Phase II: Fundamentals	Week 3	Week 4
Wall jump	25 s	30 s
Tuck jump	25 s	30 s
Jump, jump, jump, vertical jump	5 reps	8 reps
Squat jump	15 s	20 s
Single-leg barrier hop side-to-side*	25 s	30 s
Single-leg barrier hop forward-back*	25 s	30 s
Scissors jump	25 s	30 s
Single-leg hop* (hold 5 s)	5 reps	5 reps
Bounding for distance	1 run	2 runs
Phase III: Performance	Week 5	Week 6
Wall jump	25 s	20 s
Jump up, down, 180°, vertical	5 reps	10 reps
Squat jump	25 s	25 s
Mattress jump side-to-side	30 s	30 s
Mattress jump forward-back	30 s	30 s
Single-leg hop, hop, hop, stick*	5 reps	5 reps
Jump into bounding	3 runs	4 runs

* Repeat on both sides for duration or repetitions listed.

2.12. Statistical Analyses

All data were normally distributed (Kolmogorov-Smirnov test). One-tailed paired *t* tests were used to determine whether significant differences existed between pre-train and post-train test results. Chi-square tests were used to determine the difference in the distribution of athletes who had <40%, 40%–60%, 61%–80%, and >80% normalized knee separation distance on landing. Effect sizes (ES) were calculated and interpreted according to Cohen's standards [57] where ≤0.2 was considered small; 0.21–0.79, moderate; and ≥0.8, large. The ACL crude incidence rate ratios were calculated for the trained and control groups per 1000 AE and tested for significance. In addition, Fisher's exact test was conducted to determine whether the proportion of injuries in the trained group was significantly difference from the proportion of injuries in the control group. For all analyses, the level of significance was set at 0.05.

3. Results

3.1. Compliance with Training

All athletes completed at least 14 of the 18 training sessions (mean, 15 ± 1). There were no injuries sustained that caused any athlete to stop training. Because each session was supervised, all athletes completed all jumps and sports-specific drills and exercises.

3.2. Video Drop-Jump

After training, statistically significant improvements and large ES were found in the absolute cm of knee separation distance and in the normalized knee separation distance values (Table 4).

Table 4. Effect of training on video drop-jump test.

	Pre-Train *	Post-Train *	Difference *	*p* Value	Effect Size
Knee separation distance (cm)	20 ± 8 (range, 6–56)	27 ± 8 (range, 9–57)	8 ± 8 (range, −19–41)	<0.0001	0.87
Normalized knee separation distance (%)	47 ± 19 (range, 14–150)	65 ± 18 (range, 21–118)	18 ± 19 (range, −53–92)	<0.0001	0.97

* Values shown are mean ± standard deviation.

Before training, approximately 80% of the athletes had a distinctly abnormal lower limb valgus alignment position on landing (empirically designated as ≤60% normalized knee separation distance). After training, 60% of the athletes displayed a neutral position on landing. The distribution of the athletes before and after training according to four normalized knee separation distance categories is shown in Figure 1. The change in the distribution of athletes in these categories between the pre-train and post-train tests was statistically significant ($p < 0.0001$). An athlete example is shown in Figure 2.

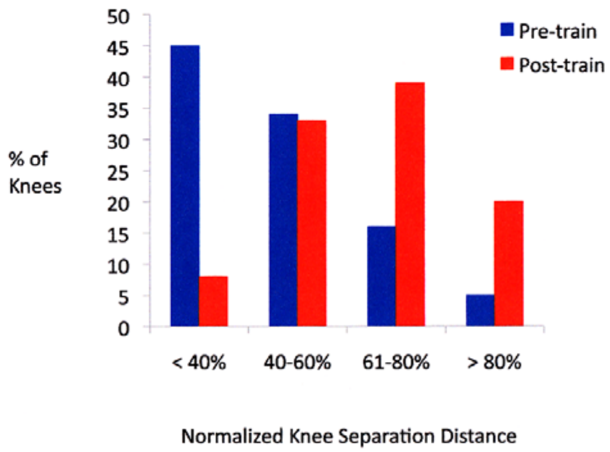
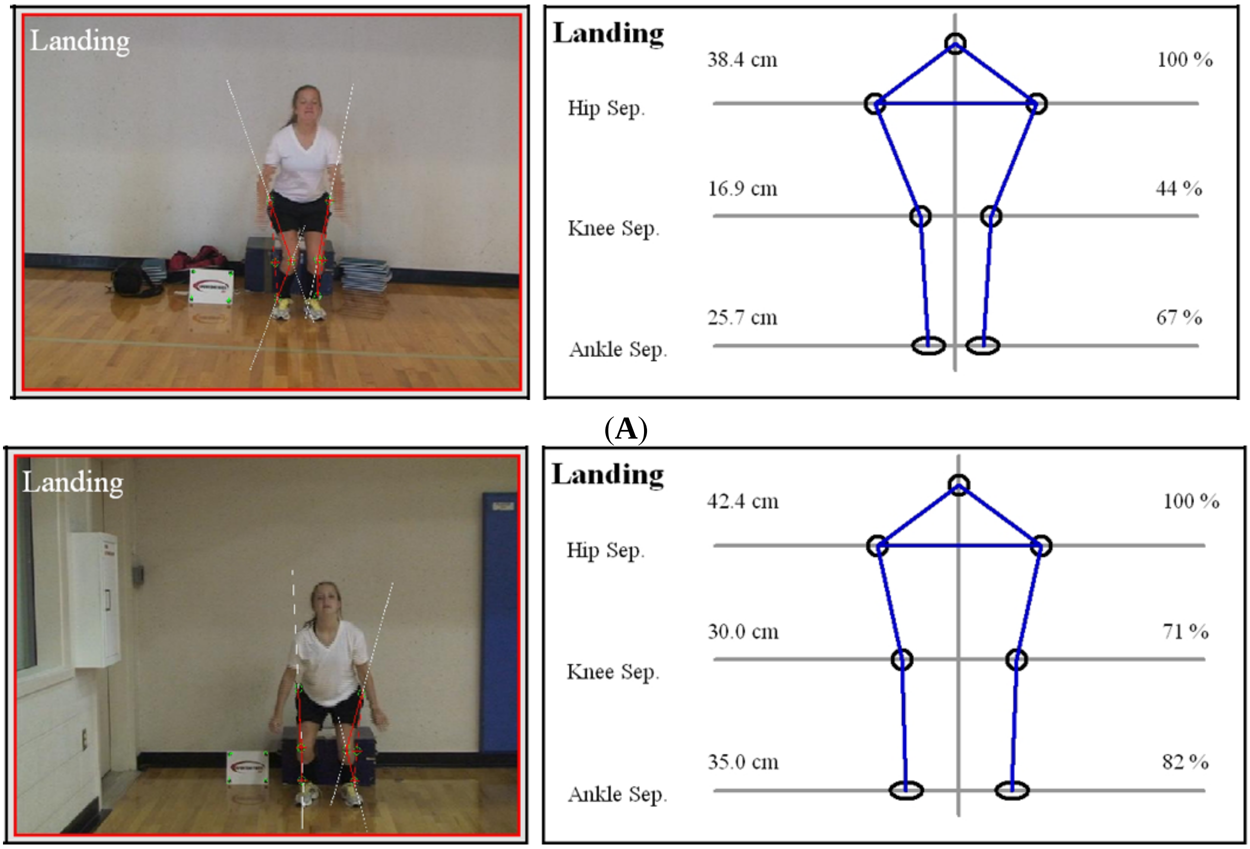


Figure 1. Results of video drop-jump test.



(**B**)

Figure 2. (**A**) Before training, this adolescent female athlete demonstrated a distinctly abnormal lower limb alignment, with a normalized knee separation distance of 44%; (**B**) After training, the athlete markedly improved her lower limb alignment to a normalized knee separation distance of 71%.

3.3. Single-Leg Hop Tests

Statistically significant improvements were found in the mean distances hopped for both single-leg hop tests for the right and left legs (Table 5). The ES were moderate in the triple crossover hop and small in the triple (straight) hop. There was no significant difference in the mean limb symmetry between pre-train and post-train values for both hop tests. Before training, 13% had abnormal symmetry (<85%) in the triple crossover hop, whereas after training, only 2% continued to have abnormal values. In the triple hop test, 8% had abnormal values before training and 2% had these values after training.

Table 5. Effects of training on the single-leg hop tests for the right leg.

Test	Pre-Train (cm)*	Post-Train (cm)*	Difference (cm)*	*p* Value	Effect Size
Triple crossover	360 ± 71 (range, 140–523)	393 ± 69 (range, 185–555)	33 ± 54 (range, −136–261)	<0.0001	0.47
Triple straight	405 ± 96 (range, 117–554)	414 ± 95 (range, 128–602)	9 ± 48 (range, −110–164)	0.003	0.09

* Values shown are mean ± standard deviation.

3.4. Vertical Jump Tests

Statistically significant improvements were noted for the two vertical jump tests; however, the ES were small. The mean difference in the test performed without countermovement was 1.1 ± 5.9 cm and the mean difference in the countermovement test was 1.3 ± 6.5 cm ($p < 0.0001$ for both analyses). Overall, 57% of the athletes showed improvement after training.

3.5. Agility t-Test, Sprints, Multi-Stage Fitness Test, Sit-up Test

A statistically significant improvement and moderate ES (.64) was noted for the agility *t*-test between the pre-train (12.10 ± 1.01 s) and post-train (11.51 ± 0.83 s) values ($p < 0.0001$). There were no significant improvements in the sprint runs.

A statistically significant improvement and moderate ES (0.23) was found in the sit-up test ($p < 0.001$).

A statistically significant improvement and moderate ES (.57) was noted for the MSFT between the pre-train (36.4 ± 5.0 VO_2max) and post-train (39.2 ± 4.8 VO_2max) values ($p < 0.0001$).

3.6. Isokinetic Test

Statistically significant improvements and moderate ES were found for the hamstrings, quadriceps, and hamstrings/quadriceps ratio on the isokinetic strength test on both the dominant (preferred kicking leg) and nondominant sides (Table 6).

Table 6. Effect of training on isokinetic quadriceps and hamstrings strength at 300°/s.

Test	Pre-Train *	Post-Train *	Difference *	*p* Value	Effect Size
Hamstrings Dominant	29 ± 6 (range, 10–45)	33 ± 8 (range, 15–73)	4 ± 7 (range, −9–53)	<0.0001	0.57
Hamstrings Nondominant	27 ± 6 (range, 14–43)	31 ± 7 (range, 9–56)	4 ± 6 (range, −8–32)	<0.0001	0.61
Quadriceps Dominant	35 ± 7 (range, 15–56)	37 ± 8 (range, 17–67)	2 ± 7 (range, −16–32)	0.001	0.27
Quadriceps Nondominant	35 ± 7 (range, 16–57)	38 ± 10 (range, 6–103)	3 ± 9 (range, −17–60)	0.0001	0.35
Ham/Quad Ratio Dominant	83 ± 17 (range, 44–163)	90 ± 24 (range, 54–272)	7 ± 27 (range, −88–206)	0.001	0.34
Ham/Quad Ratio Nondominant	78 ± 18 (range, 38–145)	83 ± 19 (range, 39–191)	5 ± 23 (range, −59–131)	0.006	0.27

* Values shown are mean ± standard deviation.

3.7. Noncontact ACL Injury Rate

The 700 trained athletes had 36,724 AE and the 1120 control athletes had 61,244 AE. There was one noncontact ACL injury in the trained group and 13 in the control group. The difference in the ACL injury incidence rates (per 1000 athlete-exposures) between the trained and control athletes was statistically significant (0.03 and 0.21, respectively, $p = 0.03$).

4. Discussion

The major finding of this investigation is that the ACL neuromuscular retraining program both significantly decreased the incidence of noncontact ACL injuries and improved athletic performance indicators in adolescent female athletes. This study entailed the largest cohort published to date in which athletic performance indices were measured after completion of ACL prevention neuromuscular training. Problems with training compliance have been addressed by others [14,15] and it has been suggested that an incentive to improve these issues is evidence that the program will improve athletic performance indicators. Although other ACL injury prevention training programs have improved certain athletic performance indices such as lower extremity muscle strength [58–63], vertical jump height [64–67], and distance hopped on single-leg tests [65,68,69], none of these programs also significantly reduced the noncontact ACL injury rate.

Since the first publication of a knee ligament injury prevention training program for female high school athletes appeared in the sports medicine literature in 1996 [22], at least 50 have followed that focused on this population [70]. A recent systematic review of all published ACL prevention training programs in female athletes aged 19 or younger found that only three programs (Sportsmetrics [23], Prevent Injury and Enhance Performance Program [PEP] [71], and Knee Injury Prevention [KIPP] [72]) significantly reduced the noncontact ACL injury rate as determined by athlete-exposures [20]. To our knowledge, no study has determined if the KIPP program improves athletic performance indices. An independent investigation of the PEP program demonstrated significant increases in electromyographic muscle peak torque and average power data (hip abduction, hip extension, knee flexion) after eight weeks of training in a group of 11 female high school athletes [73]. There was no significant improvement in jump height. Another study of the PEP program reported no benefit from the program on agility tests or vertical jump height in 31 female adolescent soccer players [74]. Although improvements were reported in sprint times during the first six weeks of training, these improvements reverted back to baseline values by 12 weeks [74].

Several ACL intervention programs have not been successful in significantly reducing noncontact ACL injury rates in adolescent female athletes [75–79]. It is important to note that some programs did reduce the incidence of lower limb injuries [75], acute knee injuries [78], contact knee injuries [78], and contact combined with noncontact ACL injuries [79]. Issues pertaining to poor compliance with training and limited statistical power due to the small number of exposures and noncontact ACL injuries were commonly cited as the reasons for the outcomes of prior investigations. Some investigators concluded that coach-led instruction, with no control on the quality of instruction or progression of exercises, was not the most desirable method in which to conduct training [77,79]. Shultz *et al.* [15] noted the importance of feedback that emphasizes correct form and technique, along with positive motivation of the athlete during training. We believe supervision is a vital component, especially in athletes that demonstrate potentially dangerous landing and cutting techniques that are believed to increase the risk of a noncontact ACL injury, such as low knee and hip flexion angles and landing flatfooted, with the foot far away from the center of body mass [80–83]. During training, athletes were constantly reminded to land softly with high knee flexion when jumping, to decelerate using small quiet steps, and to stop during sprinting drills with as little impact as possible. In addition, exaggerated knee flexion was stressed in order to avoid an extended or hyperextended position. Although not measured in our current study, we and many investigators have noted decreased ground-reaction forces and improved lower extremity alignment on landing and during cutting when these techniques are used that may decrease the risk of lower extremity injury [22,33,84–87].

For this study, we excluded any athlete with a history of a noteworthy knee injury such as a ligament rupture, meniscus tear, or patellar dislocation from training. However, in our practice, we encourage patients who wish to resume high-risk athletics such as soccer and basketball after ACL reconstruction and other major knee operations to complete this neuromuscular retraining program as end-stage rehabilitation. The criteria patients must demonstrate in order to begin training are completion of a running/agility program, completion of a basic plyometric program, negative pivot shift test, ≤3 mm increased anteroposterior displacement on the Lachman test, full range of knee motion, ≤15% deficit peak torque hamstrings and quadriceps isokinetic test, ≤15% deficit in distance hopped on single-leg hop tests, and no pain, swelling, or giving-way with any activity [88].

A limitation of this study is the difference in the number of athletes who completed the various tests before and after training to measure athletic performance indices. Isokinetic testing was conducted initially in all athletes because they were tested in our laboratory. However, over time, it became apparent that testing needed to be performed at the training sites because many athletes were unable to travel to our facility. The sprint tests were designated for soccer and basketball players only. The MSFT was introduced in the fourth year of data collection. Not all athletes completed all 18 training sessions, or completed both pre-train and post-train testing, because of reasons such as illness, time constraints, or schedule conflicts. Even so, the strengths of this study are the large number of athletes that participated in the program, the major training components remained constant throughout the multi-year study period, and there was a sufficient number of AE and noncontact ACL injuries to prevent a type II statistical error.

Many issues and questions remain regarding the gender disparity in noncontact ACL injury rates and others have offered multiple suggestions for future research directions [15,16]. Although it is well appreciated that a gender disparity exists among high school and collegiate male and female athletes, the exact reasons remain unknown. Large-scale, multifactorial studies are required on all potential risk factors for this injury that include anatomical, structural, genetic, hormonal, climate, and equipment. Secondly, it is uncertain if all female athletes should undergo a neuromuscular training program such as the one in this investigation. Once a hierarchy of risk factors is known, the identification of highly sensitive and practical screening tools to target those athletes at greatest risk for injury would be of tremendous benefit.

5. Conclusions

An ACL prevention neuromuscular retraining program was developed and conducted in 1,000 female athletes aged 13–18 years. The program resulted in statistically significant improvements in overall lower limb alignment on a drop-jump test, distance hopped in single-leg hop tests, agility on the *t*-test, estimated VO_2max on the multi-stage fitness test, and isokinetic hamstrings and quadriceps strength. The trained athletes had a significant reduction in the noncontact ACL injury incidence rate compared with the control group. The neuromuscular retraining program was effective in reducing noncontact ACL injury rate and improving athletic performance indicators.

Acknowledgments

We thank Stephanie Smith, Thomas Campbell, Catherine Walsh, Michelle Brock, Jennifer Riccobene, and Cassie Fleckenstein for their assistance with data collected for this study. We also thank Martin Levy for his assistance with the statistical analysis regarding ACL injury rates. This study was funded by the Noyes Knee Institute and the Cincinnati Sportsmedicine Research and Education Foundation, Cincinnati, OH, USA.

Author Contributions

FN designed the major components of the Sportsmetrics program and designed the investigation. SBW and FN collectively determined the tests to conduct, statistically analyzed the test data and the literature published to date, and wrote the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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