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NEUROMUSCULAR TRAINING IMPROVES PERFORMANCE AND LOWER-EXTREMITY BIOMECHANICS IN FEMALE ATHLETES

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[1]Cincinnati Children's Hospital Research Foundation Sports Medicine Biodynamics Center and Human Performance Laboratory, Cincinnati, Ohio, 45229; [2]Departments of Pediatrics and Orthopaedic Surgery, The University of Cincinnati College of Medicine, and Department of Rehabilitation Sciences, the College of Allied Health Sciences, Cincinnati, Ohio 45267.

ABSTRACT. Myer, G.D., K.R. Ford, J.P. Palumbo, and T.E. Hewett. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J. Strength Cond. Res. 19(1):51–60. 2005.*—The purpose of this study was to examine the effects of a comprehensive neuromuscular training program on measures of performance and lower-extremity movement biomechanics in female athletes. The hypothesis was that significant improvements in measures of performance would be demonstrated concomitant with improved biomechanical measures related to anterior cruciate ligament injury risk. Forty-one female basketball, soccer, and volleyball players (age, 15.3 ± 0.9 years; weight, 64.8 ± 9.96 kg; height, 171.2 ± 7.21 cm) underwent 6 weeks of training that included 4 main components (plyometric and movement, core strengthening and balance, resistance training, and speed training). Twelve age-, height-, and weight-matched controls underwent the same testing protocol twice 6 weeks apart. Trained athletes demonstrated increased predicted 1 repetition maximum squat (92%) and bench press (20%). Right and left single-leg hop distance increased 10.39 cm and 8.53 cm, respectively, and vertical jump also increased from 39.9 ± 0.9 cm to 43.2 ± 1.1 cm with training. Speed in a 9.1-m sprint improved from 1.80 ± 0.02 seconds to 1.73 ± 0.01 seconds. Pre- and posttest 3-dimensional motion analysis demonstrated increased knee flexion-extension range of motion during the landing phase of a vertical jump (right, 71.9 ± 1.4° to 76.9 ± 1.4°; left, 71.3 ± 1.5° to 77.3 ± 1.4°). Training decreased knee valgus (28%) and varus (38%) torques. Control subjects did not demonstrate significant alterations during the 6-week interval. The results of this study support the hypothesis that the combination of multiple-injury prevention-training components into a comprehensive program improves measures of performance and movement biomechanics.

KEY WORDS. knee-injury prevention training, ACL, female sports, dynamic neuromuscular training, knee valgus moment

INTRODUCTION

Marked evidence shows that neuromuscular training programs are effective for improving measures of performance. The benefits of a program designed for performance enhancement often include increased power, agility, and speed (25, 26, 46). Female athletes may especially benefit from multicomponent neuromuscular training because they often display decreased baseline levels of strength and power compared with their male counterparts. Comprehensive neuromuscular training programs designed for young women may significantly increase power, strength, and neuromuscular control and decrease gender differences in these measures (26, 27). 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) (10, 12, 22, 39). These ancillary effects of neuromuscular training, which are likely related to the reduction of the risk of injury in female athletes, are positive results of training. Without the performance-enhancement training effects, however, athletes may not be motivated to participate in a neuromuscular training program. It has not been demonstrated in the literature that performance-enhancement and injury-prevention training effects can be reached through a single neuromuscular training protocol. If such a program design were widely available, prevention-oriented training could be instituted on a widespread basis with highly motivated athletes.

The purpose of this study was to examine the effects of a comprehensive neuromuscular training program on measures of performance and lower-extremity biomechanics in female athletes. The hypothesis was that significant improvements in measures of performance, specifically vertical jump, single-leg hop distance, speed, bench press, and squat, would be demonstrated concomitant with improved biomechanical (increased range of motion [ROM] and decreased knee varus and valgus torques) measures related to injury risk in female athletes.

METHODS

Experimental Approach to the Problem

A controlled cohort repeated-measures experimental design was used to quantify the effects of the neuromuscular training intervention on subjects in this study. Control and experimental subjects were pretested 1 week before the initial training session. Posttesting was performed approximately 7 weeks after the pretest on control and experimental subjects (4 days after the final training session). Two certified strength and conditioning specialists and 2 graduate level interns conducted all training. Experimental subjects were placed into 2 groups, which allowed for 2 identical training sessions per day. The Cincinnati Children's Hospital Medical Center Institutional Review Board approved this study.

Subjects

Fifty-three female athletes from Cincinnati-area high schools participated in this study. The mean ± *SD* age of the participants was 15.3 ± 0.9 years (control age, 16.5 ± 1 years) with a range of 13–17 years. The subjects were asked to list their primary sport; 15 reported basketball, 19 reported soccer, and 19 reported volleyball. Seventy-five percent of the subjects had at least 6 years of experience in their reported sport, whereas only 1% had less than 4 years experience (2–4 years reported). Seventy-three percent of the subjects reported previous participation in some form of off-season training program. Height and weight was assessed at the pre- and post-training test dates. The initial height (mean ± *SD*) of the participants was 171.2 ± 7.21 cm, and the initial weight was 64.8 ± 9.96 kg. No statistically significant differences were found in height or weight between the control group and the trained group (control height, 168.5 ± 8.83 cm; weight, 65.6 ± 9.34 kg). Follow-up assessment of height and weight at the posttest date revealed no change in mean height, and mean weight increased in the experimental group to 65.7 ± 6.73 kg ($p = 0.01$). Parents or guardians signed informed consent before the subjects' participation in the study. Forty-one subjects were assigned to the training group and 12 subjects were assigned to an untrained control group.

Physical Performance Testing

Vertical-Jump Height Testing. The vertical jump was measured on MX1 vertical-jump trainer (MXP Sports, Reading, PA). Before the test, each subject's overhead reach was determined with the subject reaching directly overhead with both hands up toward the ball; the midline of the basketball was aligned with the distal interphalangeal joint of the right and left middle fingers. The subject was told to use a natural overhead reach (no exaggerated superior rotation of the shoulder girdle). The digital readout of the system was zeroed to subtract reach from jump height and provide actual vertical displacement during the vertical-jump testing. Each subject stood 30.5 cm behind the midpoint of the MX1 ball attachment and performed a countermovement vertical jump off both feet and grabbed the ball with both hands. The height of the MX1 was adjusted to the maximum height the subject could grab the ball and maintain the grip until landing. The ball height was raised incrementally until the subject could not pull the ball down from a height after 3 successive trials. The highest successful attempt was recorded. Previous authors have demonstrated that countermovement vertical-jump testing has a test-retest reliability of 0.993 (40).

Speed Testing. Sprint time was measured by the speed trap II timing system (Brower Timing Systems, Draper, UT). The distance from start to finish was 9.1 m and the time was measured with accuracy to 0.01 of a second. The subjects began with their toe on the start transmitter. Timing began when toe pressure was removed and ended when the subject interrupted the infrared beam. The best time of 3 trials was recorded.

Single-Leg Hop-and-Hold Distance Testing. The subject stood on 1 leg and hopped forward as far as possible, landing on the same leg. The trial was not accepted if the landing was not held for 3 seconds. The farthest distance (toe-to-toe) of 3 trials for each leg was recorded in centimeters. The reliability of hop tests has been previously demonstrated (36).

Strength Testing. Before testing, the subject was instructed on the proper form for squat and bench press exercises. The subject was instructed to perform practice repetitions with the standard barbell. After the exercise orientation, the trainer chose a weight he or she estimated that the subject could lift 5 or fewer times. The test was accepted if the repetitions completed were 8 or fewer. If the subject completed more than 8 repetitions, more weight was added and the subject was retested. The 1 repitition maximum (1RM) was predicted with the equation introduced by Wathen $\{1\text{RM} = 100 \times \text{rep wt}/[48.8 + 53.8 \times \exp(-0.075 \times \text{reps})]\}$ (30, 44). The squat testing required the subject's thigh to be parallel to the floor for each repetition. The bench press testing required the subject to touch her chest and return to full arm extension for each repetition. Kravitz and colleagues (28) demonstrated that predicted 1RM testing provided acceptable levels of accuracy.

Biomechanical Testing

Three-Dimensional Biomechanical Analysis Testing. Each subject was instrumented with 19 retroreflective markers placed bilaterally on the greater trochanter, mid thigh, medial and lateral knee (joint line), mid shank, medial and lateral ankle (malleolus), posteriorly on the calcaneous, and superiorly on the dorsal aspect of the foot (between second and third metatarsals). An additional marker on the left posterior superior iliac spine was also applied to offset the right and left side to aid the real-time identification of markers during data collection. The motion analysis system consisted of 8 digital cameras (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA) connected through an Ethernet hub to the data-collection computer (Dell Computer Corporation, Round Rock, TX) and sampled at 300 Hz. Two force platforms (Advanced Mechanical Technology, Inc., Watertown, MA) were sampled at 1,000 Hz and time was synchronized to the motion analysis system. Data were collected with EvaRT (Version 3.21, Motion Analysis Corporation) and imported into KinTrak (Version 6.2, Motion Analysis Corporation) for data reduction and analysis. Before each data-collection session, the motion analysis system was calibrated to manufacturer recommendations.

A static trial was collected to align the joint coordinate system to the laboratory. The subject was instructed to stand still and was aligned as closely with the laboratory coordinate system as possible. The medial leg markers were subsequently removed before the drop vertical jump (DVJ) trials. The DVJ trials started with the subject on top of a box (31 cm in height) with her feet positioned 35 cm apart from each other (distance between toe markers). The subject was instructed to drop directly down off the box and immediately perform a maximum vertical jump, raising both arms as if she were jumping for a basketball rebound. The DVJ has been shown to have high within-session and between-session reliability (13, 14). The 2 force platforms were embedded into the floor and positioned 8 cm apart so that each foot would contact a different platform during the maneuver. The first contact on the platforms (i.e., the drop from the box) was used for analysis. Three successful trials were recorded for each subject. Three-dimensional marker trajectories were estimated by the direct linear transformation method and filtered through a low-pass Butterworth digital filter at a cutoff frequency of 12 Hz (45). Knee joint flexion-extension angles for the right and left leg were calculated from an embedded joint coordinate system (18). Knee joint varus and valgus torques were calculated from the motion and force data with inverse dynamics (45). Net internal (muscular) torques are described in this study and represent the body's response to external forces.

Training Procedures

The neuromuscular training program used in this study was a synthesis of findings derived from published research studies and prevention techniques (7, 16, 19–22, 24–26, 29). The components of the dynamic neuromuscular training protocol tested in this study included plyometrics and movement training, core strengthening, balance training, resistance training, and interval speed training. Each component of the training focused on comprehensive biomechanical analysis by the instructor, with feedback given to the subject both during and after training. The training protocol stressed technique perfection for each exercise, especially in the early training sessions. The trainers were skilled in recognizing the desired technique for a given exercise and consistently encouraged the subject to maintain proper technique performance for as long as possible. When the subject fatigued to a point that she could not perform the exercise with near-perfect technique, the exercise was stopped. The subject recorded the duration and repetitions completed. The goal of the next training session was to continue to improve technique while increasing duration, volume, or intensity of the exercise. The progressive nature of the neuromuscular training was important to achieve successful outcomes from the training. The neuromuscular training stressed performance of athletic maneuvers in a powerful, efficient, and safe manner.

The training program was conducted on Tuesday, Thursday, and Saturday. Each training session lasted for approximately 90 minutes. Before each training session, an active warm-up that included jogging, backwards running, lateral shuffling, and carioca was used. Tuesday training included a 30-minute plyometric station, a 30-minute strength station, and a 30-minute core-strengthening and balance station. Thursday training included a 30-minute plyometric station, a 30-minute speed station, and a 30-minute strengthening and balance station. Saturday training included a 45-minute speed station and a 45-minute strength station. At the end of each training session, the subjects performed self-selected stretching exercises for 15 minutes. The training period lasted a total of 6 weeks.

The plyometrics and dynamic-movement training component progressively emphasized double- then single-leg movements through training sessions (Table 1; 22). The majority of the initial exercises involved both legs to safely introduce the subjects to the training movements. Early training emphasis was on sound athletic positioning that may help create dynamic control of the subject's center of gravity (34). Soft, athletic landings that stressed deep knee flexion were used by the trainer, with verbal feedback to make the subject aware of biomechanically unsound and undesirable positions. Progressively, a greater number of single-leg movements were introduced while the focus on correct technique was maintained. For example, the single-leg crossover hop-and-hold exercise was used as an important exercise to teach single-leg landings (Figure 1). Later training sessions used explosive double- and single-leg movements that focused on maximal performance in multiple planes of movement. Volume of the initial plyometric bouts was low because of extensive technique training that was required along with the subject's decreased ability to perform the exercise with proper technique for the given durations. Volume was increased as technique improved to the midpoint of training, after which a progressive decrease in volume was followed for the final sessions to allow for increased training intensity (22).

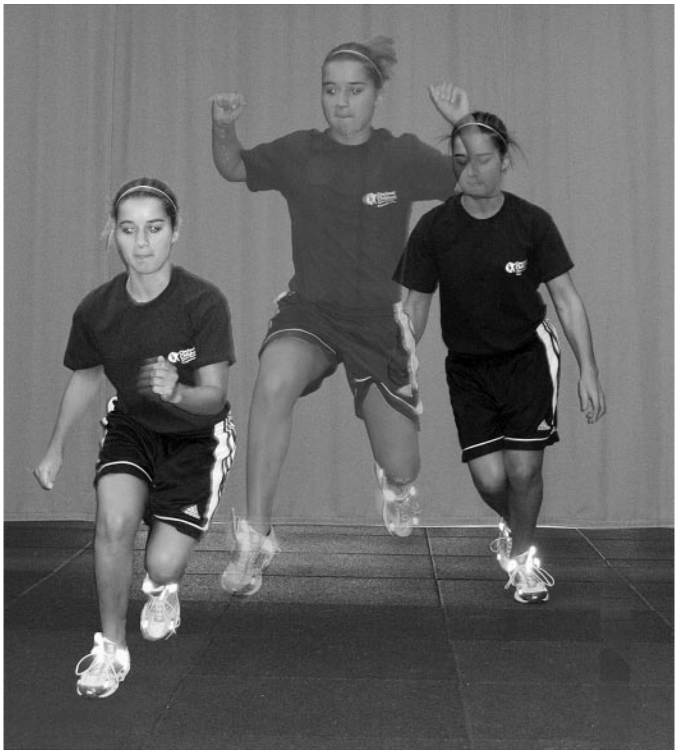

FIGURE 1. Crossover hop, hop, hop, stick. In this exercise the athlete starts on a single limb and jumps at a diagonal across the body, lands on the opposite limb with the foot pointing straight ahead, and immediately redirects the jump in the opposite diagonal direction. Train this jump with care to protect your athlete from injury.

An important component to the final progressions of the plyometric and movement training used unanticipated cutting movements during training. Single-faceted sagittal-plane training and conditioning protocols that do not incorporate cutting maneuvers will not provide similar levels of external varus and valgus or rotational loads that are seen during sport-specific cutting maneuvers (32). Training programs that incorporate safe levels of varus and valgus stress may induce more "muscle dominant" neuromuscular adaptations (31). Such adaptations can better prepare an athlete for more multidirectional sport activities, which can improve their performance and reduce risk of lower-extremity injury (6, 21, 22). Female athletes perform cutting techniques with increased valgus angles (33). Knee valgus loads can double when performing unanticipated cutting maneuvers similar to those used in sport (3). The endpoint of the training was designed to reduce anterior cruciate ligament (ACL) loading via valgus torque reduction, which may be gained by training the athlete to use movement techniques that produce the low-abduction knee joint torques (31). Additionally, by improving reaction times to provide more time to

Table 1. Example of plyometrics and movement-training component from 1 session.*

Exercise	Sets	Time or repetitions (reps)
Wall jumps (ankle bounces)	1	15 s
Squat jumps (frog jumps)	1	10 s
Tuck jump (with abdominal crunch)	1	10 s
Barrier jumps (front to back) speed	1	15 s
Barrier jumps (side to side) speed	1	15 s
Crossover hop, hop, hop, stick (right to left)†	1	6 reps
180° jumps (speed)	1	15 s
Broad jump, jump, jump, vertical	1	6 reps
Jump into bounding	1	6 reps
Forward barrier hops with staggered box	1	6 reps
Lateral barrier hops with staggered box	1	6 reps
Box depth-180°-box depth-max vertical	1	8 reps
BOSU 180° jumps stick landing	1	15 reps

* Training component taken from the third week (Tuesday and Thursday session) of the neuromuscular training program.

† Crossover hop, hop, hop, stick is depicted in Figure 1.

Table 2. Example of resistance-training component from 1 session.*

Exercise	Sets	Repetitions
DB hang snatch	2	8
Squat	2	8
Bench press	2	8
Leg curl	2	8
Shoulder press	2	8
Lat pull-down	2	8
Assisted Russian hamstring curl†	2	15
Back fly	2	12
Bicep circuit	1	12
Ankle: plantar-dorsi	1	12

* Training component taken from the third week (Thursday and Saturday session) of the neuromuscular training program.

† Assisted Russian hamstring curl is depicted in Figure 2.

voluntarily precontract the lower-extremity musculature and make appropriate kinematic adjustments, ACL loads may be reduced during athletic maneuvers (3, 35).

Before teaching unanticipated cutting, the subjects in this study were first taught to proficiently attain proper athletic position. The athletic position is a functionally stable position with the knees comfortably flexed, shoulders back, eyes up, feet approximately shoulder-width apart, and body mass balanced over the balls of the feet. The subjects were taught to keep their knees over the balls of the feet and keep their chest over the knees (22). This was the athlete-ready position and was the starting and finishing position for most of the training exercises. This was also the goal position before initiating a directional cut. The trainer added the directional cues to the unanticipated part of training by pointing out a direction in a more sports-specific manner and by using partner-mimic or ball-retrieval drills. The goal portion of the training was to teach the subject to use safe cutting techniques in unanticipated sport situations, which might instill technique adaptations that will more readily transfer onto the field of play.

The resistance-training component was progressed from an initial high-volume and low-intensity protocol to a low-volume and high-intensity protocol. The initial training intensity was set at approximately 60% of the subject's pretested predicted 1RM. Exercise order progressed from multijoint exercises to alternating upper- and lower-body exercises (Table 2). Trainers prescribed the weight to be used before each training session for each subject. The subjects recorded the number of repetitions achieved after each completed set. The weight to be used was increased before each training session if the required number of repetitions was achieved to ensure appropriate intensity progression. The emphasis for intensity selection was proper technique and safety. If technique was not near perfect, then the weight was lowered until proper technique could be restored. The assisted Russian hamstring curl was an important exercise included in the training and focused on correcting the low hamstring strength levels common to female athletes (22, 23). Figure 2 shows the trainer-assisted performance of this technique. The goal of the resistance-training component of the protocol was to strengthen all major muscle groups through the complete ROM and to provide complementary muscular strength and power to the plyometric and speed components of the protocol.

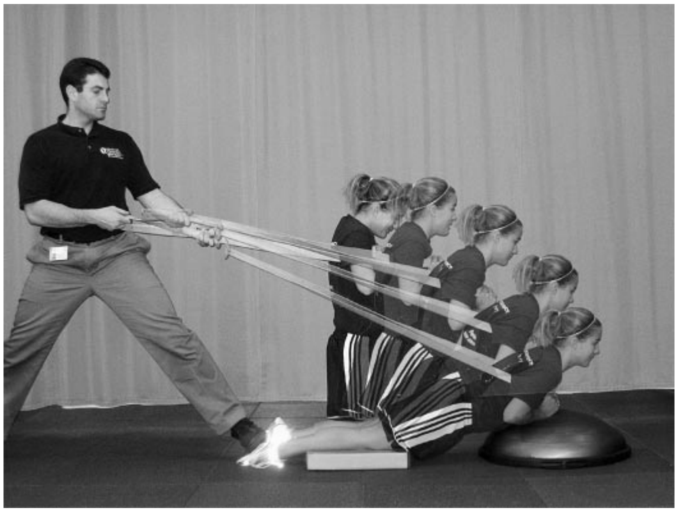

Figure 2. Assisted Russian hamstring curl. In this exercise the trainer anchors the athlete by standing on the athlete's feet and provides lift assistance with a strap that is attached around the chest. The athlete performs full eccentric and concentric movement with the assistance of the trainer.

The core strengthening and balance training component of the protocol (Table 3) followed an organized exercise selection specifically directed at strengthening the core stabilizing muscles. This component focused on providing an appropriate balance between developing the proprioceptive abilities of the subject and exposing the subject to inadequate joint control. The training progression took the subject through a combination of low- to higher-risk maneuvers in a controlled situation. The intensity of the exercises were modified by changing the arm position, opening and closing eyes, changing support stance (Figure 3), increasing or decreasing surface stability with balance training device (BOSU Balance Trainer, DW Fitness LLC, Madison, NJ) (Figure 4), increasing or decreasing speed, adding unanticipated movements or perturbations, and adding sports-specific skills. The goal of the functional balance training and core strengthening was to bring the subject to a level of core stability and

TABLE 3. Example of core strength and balance-training component from 1 session.*

Exercise	Sets	Time or repetitions (reps)
Broad jump–stick landing	1	4 reps
Crossover hop-stick	1	12 reps
Single-leg × hop	1	5 reps
Box drop medicine ball catch	1	8 reps
180° Jumps stick landing–medicine ball catch	1	6 reps
BOSU double-leg perturbations	2	20 s
BOSU both knees deep hold–medicine ball catch	2	20 reps
BOSU double-leg pick	1	10 reps
BOSU single-leg deep hold	2	20 s
BOSU crunches	1	55 s
Double crunch	2	25 reps
BOSU V-sit–toe touches	1	15 reps
BOSU swivel crunch (feet up)	2	30 reps
BOSU superman (right to left)	1	20 reps

* Training component taken from the third week (Tuesday and Thursday session) of the neuromuscular training program.

FIGURE 3. Support variations. A pictorial display of different support stances on unstable surfaces that are used in the core strengthening and balance training.

coordination that allowed her to properly reduce force, maintain balance and posture, and subsequently regenerate force in the desired direction.

The final component of the protocol was speed training (Table 4). The speed component of the training used interval partner-resistive band running. Two medium bands (Jump Stretch Inc., Youngstown, OH) were tied together and anchored around the waist of partnered subjects (Figure 5). The subject in the forward position was instructed to very quickly transition from this starting stance to run with proper biomechanics for the allotted time period. The trailing subject provided a light, medium, or heavy resistance as instructed by the trainer. During the initial session, the trainer instructed the subjects on how to vary the desired resistance. Trainers provided biomechanical feedback during each training bout. The final run of each session included a nonresisted maximum-effort run of varying distance. The goals of the interval speed-training component were improved running mechanics, improved short-distance speed, explosiveness, and increased muscular resistance to fatigue.

Statistical Analyses

Statistical means and *SEM* for each variable were calculated for each subject. Student's *t*-tests were used to compare pre- and posttest values for the control and training groups to determine statistical significance. A Bonferroni correction was applied to statistical comparisons to correct for possible inflation of the overall type I error rate, resulting in an alpha level of <0.005 being required for statistical significance. Statistical analyses were conducted in SPSS (SPSS for Windows, Release 10.0.7, SPSS Inc., Chicago, IL). The pre-established compliance criterion required that each participant be present for at least two-thirds (12 of 18) of the training sessions to be included in the study.

RESULTS

The effects of the 6-week comprehensive neuromuscular training on measures of strength and power are presented in Figure 6. The mean predicted 1RM squat improved 92% (34.2 ± 1.1 kg to 65.7 ± 1.9 kg; $p < 0.001$) and the

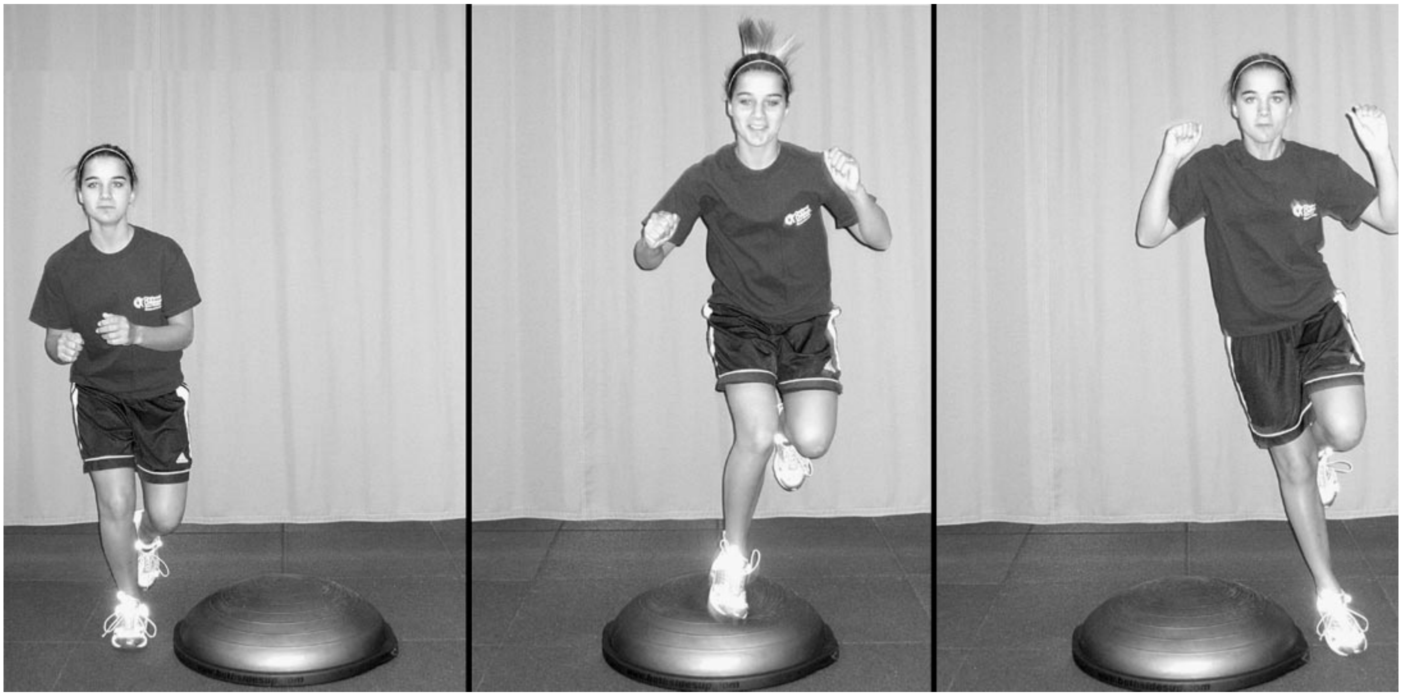

FIGURE 4. BOSU lateral hop. An advanced exercise that demonstrates single-limb stance support on surfaces of varying stability. The athlete is instructed to hold each position for 3 seconds before hopping to next stance position. Deep knee flexion is stressed when performing this exercise.

TABLE 4. Example of speed-training component from 1 session.*

Exercise	Sets	Time (sec)
Jog to sprint	1	10
Run (light resistance)	1	12
Run	1	10
Backwards	2	15
Run/drum majors/run (light resistance)	1	4/6/4
Run (medium resistance)	1	6
Run (medium resistance)	2	6
Run (heavy resistance)	1	6
Run (heavy resistance)	2	6
Run	1	10

* Training component taken from the third week (Thursday and Saturday session) of the neuromuscular training program. Example of resisted run is depicted in Figure 5.

bench press improved 20% (32.0 ± 0.6 kg to 38.4 ± 0.8 kg; $p < 0.001$). Figure 7 shows the pre- and posttest comparison of single-leg hopping distance. Right and left single-leg hop distance increased 10.4 and 8.5 cm (right, 165.1 ± 3.0 cm to 175.5 ± 2.6 cm; left, 165.1 ± 2.7 cm to 173.6 ± 2.5 cm; $p < 0.001$), respectively. Double-leg vertical jump also increased from 39.9 ± 0.9 cm to 43.2 ± 1.1 cm ($p < 0.001$). Trained women demonstrated significantly lower sprint times than before training on average. Speed in the 9.1-m sprint improved from a mean pretest value measure of 1.80 ± 0.02 seconds to a mean posttest measure of 1.73 ± 0.01 seconds ($p < 0.001$).

The study subjects demonstrated significant biomechanical changes during a landing maneuver after the training concomitant with the performance improvements. Measurements taken from the subjects with a 3-dimensional motion analysis system were used to calculate absolute knee ROM during landing from a box DVJ. The knee joint ROM was calculated during the stance phase after the drop off the box and immediately before maximum vertical jump. Knee flexion-extension ROM during the landing phase of a box drop into a vertical jump increased from 71.9 ± 1.4° to 76.9 ± 1.4° ($p < 0.001$) for the right knee and 71.3 ± 1.5° to 77.3 ± 1.4° ($p < 0.001$) for the left knee. Calculation of time on the force platform was not different between pre- and posttest.

FIGURE 5. Partnered resisted speed training. Representative photograph of the resisted speed training. Proper biomechanics must be maintained when training for speed with resistance.

Before training, subjects demonstrated large medial-lateral knee torques on landing. Knee varus and valgus torques (average of the 3 trials) for the right and left side

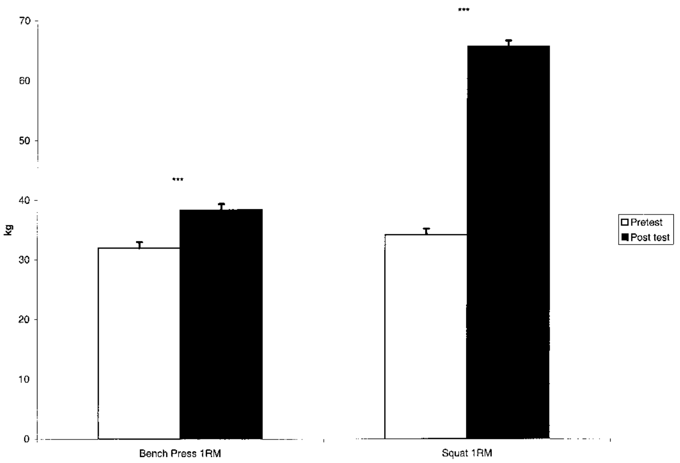

FIGURE 6. Pre- and posttraining measures of bench press and squat. Predicted 1 repetition maximum (kg) measurement of pre- and posttest bench press and squat exercises. Posttest measurements were significantly greater in both exercises ($p < 0.001$).

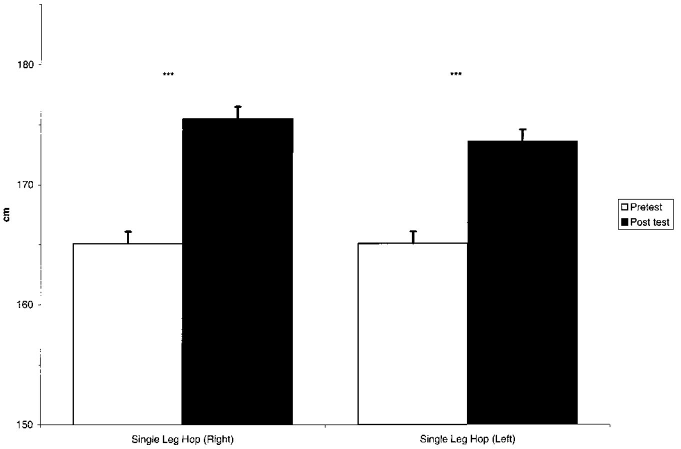

FIGURE 7. Pre- and posttraining measures of right and left single-leg hop distance. Single-leg hop distance (cm) for the right and left side. Posttest distances were significantly greater on both sides ($p < 0.001$).

were calculated in these female athletes pre- and posttraining. Untrained subjects displayed significantly higher maximum varus and valgus knee torque than after training on their right side. After training, the subjects showed significantly lower torques (Figure 8). The right knee internal valgus torque decreased 28% (60.4 ± 5.5 N-m to 43.4 ± 3.3 N-m; $p < 0.001$), whereas right knee internal varus torque decreased 38% (34.0 ± 2.8 N-m to 21.1 ± 1.7 N-m; $p < 0.001$). Left knee varus and valgus torques showed a trend toward a decreased valgus torque ($p = 0.08$ and $p = 0.085$), though this decrease was not statistically significant. The control group demonstrated no significant increase in any of the above measured parameters after the 6-week trial period. The control groups demonstrated high test-retest reliability intraclass correlation coefficient [3,1] measures (bench press $R = 0.94$; squat $R = 0.98$; vertical jump $R = 0.91$; speed $R = 0.93$; knee ROM $R = 0.89$; varus moments $R = 0.68$; valgus moments $R = 0.74$).

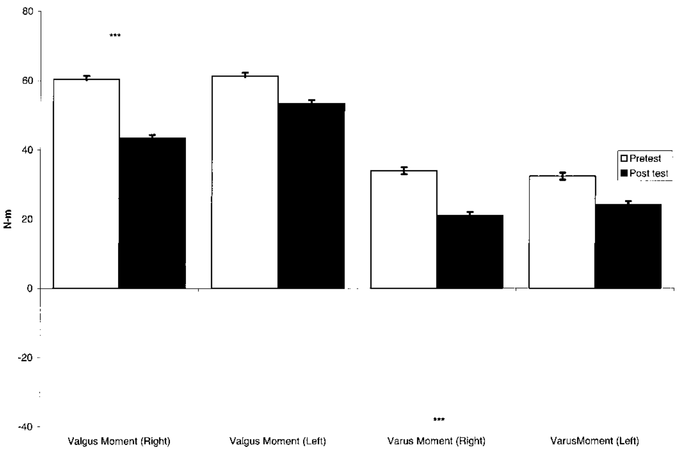

FIGURE 8. Knee varus and valgus torques. Knee joint maximum valgus and maximum varus torques were significantly reduced in the right side after the training program ($p < 0.001$). A trend was present in the left side (valgus, $p < 0.08$; varus, $p < 0.085$) for a reduction in varus and valgus torques; however, this difference was not statistically significant.

DISCUSSION

A comprehensive neuromuscular training program designed for the prevention of lower-extremity injuries can provide simultaneous improvements in athletic performance and movement biomechanics in female athletes. Subjects who underwent the 6-week protocol outlined in this study were able to improve measures of vertical jump, single-leg hop distance, speed, bench press, squat, knee ROM, and knee varus and valgus torques compared with their pretrained values and with an untrained control group. The demonstrated improvements were both statistically and clinically (functionally) significant (up to 92% improvement).

These results support the work of Hewett et al. (22), who used a program design that focused on correction of dynamic movement patterns and muscle imbalances with technique training and lower-body plyometrics with supplemental strength training. They demonstrated that female athletes who participated in neuromuscular training demonstrated greater dynamic knee stability than did women who had not undergone training. Similar to the results demonstrated in the current study, the study subjects showed simultaneous improvements in vertical jump and decreased varus and valgus torques at the knee. Hewett et al. (21) also conducted an epidemiologic study with the purpose of prospectively evaluating the effects of the same neuromuscular training program on serious knee injury rates in female athletes. Their results demonstrated that technique-oriented plyometrics with supplemental resistance training significantly reduced serious knee injuries, including ACL injuries, in adolescent volleyball, soccer, and basketball players. The previous work of Hewett and colleagues provides a portion of the groundwork for the protocol used in the current study (21, 22). The technique principles derived from their work were probable contributors to the decrease in valgus and varus torques found in the current study. In particular, an overall technique emphasis was placed on performing jumps and landings with proper knee alignment, with athletes taught to use their knees like a hinge joint rather than a ball-and-socket joint.

The results of the present study also demonstrate that neuromuscular training that emphasizes deep knee flexion landings and stability exercises significantly alters knee biomechanics, specifically knee flexion, during the landing phase of a jump. Griffin reports the work of Henning (17) identified 3 potentially dangerous maneuvers in sport that should be modified through training to prevent ACL injury. He suggests 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 suggests a decrease in injury rates between the trained and the untrained study groups (17). Boden et al. (4) support Henning's work with a biomechanical analysis of knee injuries in which they reported a majority of ACL injuries occur when landing and cutting with the knee near extension. The potential injury prevention and improved movement mechanics substantiate the concept that deep knee flexion exercises be incorporated into athletic-development training protocols.

The effects of a sound resistance-training component on increases in strength in female athletes have been widely documented in the literature (2, 5, 8, 15). The current study found similar results, with significant increases in both bench press and squat. The effects of plyometrics may be combinatory to resistance training, similar to the results demonstrated by Adams et al. (1). They found that subjects who underwent a combined plyometric and squat training program had more significant increases in vertical jump than did subjects who trained only with squats or plyometrics alone (1). Additionally, Fatouros and colleagues (11) found the combinatory effects of plyometrics and resistance training to increase not only jump performance but also leg strength. The results of the current study showed that the increase in squat was significantly greater than the increases demonstrated in the bench press exercise ($p < 0.001$). This difference in gains may reflect the lack of upper-body plyometrics incorporated into the studied training program that may have provided additive gains in bench press 1RM. The data from the current study concur with the findings from Vossen et al. (43) that the addition of upper-body plyometrics may increase an athlete's ability to improve upper-body performance. Therefore, future protocols may include upper-body plyometrics to increase the performance gains in female athletes.

Resistance training likely reduces injury because of the beneficial adaptations that occur in bones, ligaments, and tendons after training (12, 25). Lehnhard and others (29) were able to significantly reduce injury rate with the addition of a strength-training regimen to a study group. The current results, combined with previous literature, demonstrate the necessity of resistance training in any protocol aimed at improving overall athletic performance and potentially decreasing injury risk.

Balance-board exercises significantly decreased noncontact ACL injury rates in male athletes (7). This type of proprioceptive and balance training can improve postural control, which may be related to increased risk of ankle injury (41, 42). Paterno et al. (37) demonstrated significant increases in single-leg stability with the neuromuscular training program outlined in this study. Previous literature demonstrates the importance of integrating proprioceptive stability and balance-training techniques into injury-prevention protocols. It may be hypothesized that this component of the training was related to the increased performance of the subjects to hop as far as possible and hold the difficult position of a single-limb stance.

The effects of training programs specifically targeted for speed enhancement on injury risk reduction are heretofore unknown. However, Heidt et al. (19) were able to gain injury-prevention effects through a speed and agility protocol. They were able to reduce lower-extremity injuries in the trained female athletes by 19% when compared with the athletes who did not go through training. The literature also demonstrates evidence that speed training enhances speed performance and that plyometric or resistance training can provide combinatory effects for increasing speed (9, 38). The resistance speed training emphasized that powerful first step movements may be related to the improvements in reported short-distance speed. Combined with the previous literature, this advocates its addition in comprehensive athletics developmental and injury-prevention protocols.

The results of this study provide evidence that the effects of a comprehensive training program that combines several components, including injury-prevention techniques, not only decrease the potential biomechanical risk factors of lower-extremity injury, but can also provide additive performance-enhancement effects. The effects of plyometric power, strength, core stability, and speed may be synergistic in the female athlete. Programs designed to target each aspect of athletic performance not only create the potential to achieve optimal performance, but also provide the possibility for female basketball, soccer, and volleyball players to display their peak performance ability throughout an injury-free season.

PRACTICAL APPLICATIONS

We conclude that female athletes who train with a comprehensive neuromuscular training program designed for injury prevention can gain simultaneous performance enhancement and significant improvements in movement biomechanics. Although no specific scientific evidence demonstrates that neuromuscular training improves win-loss records, evidence shows that increased performance relates to level of play (National Collegiate Athletic Association Division I, II, or III) and if the player has a starting or nonstarting position on a particular team (15). It is also likely that playing without injury enhances an athlete's productivity across his or her sports season. We suggest that off-season and preseason conditioning programs include components of plyometrics and movement training, resistance training, core strengthening, balance training, and speed training. These components may be combinatory and cumulative in their effects of increasing performance and improving lower-extremity biomechanics. If similar comprehensive neuromuscular training programs were initiated on a widespread basis, female athletes might achieve optimal performance levels through the combinatory effects of improved power, strength, speed, core stability, functional biomechanics, and reduced injury risk. In addition, if used at the right time in muscular and motor control development, even greater effects on both performance and injury risk might be achieved.

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