Neuromuscular Training Improves Single-Limb Stability in Young Female Athletes

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Study Design: Controlled single-group pretest/posttest design.
Objective: The purpose of this study was to determine if a 6-week neuromuscular training program designed to decrease the incidence of anterior cruciate ligament (ACL) injuries would improve single-limb postural stability in young female athletes. We hypothesized neuromuscular training would result in an improvement in postural stability, with the greatest improvement taking place in the medial-lateral direction.
Background: Balance training has become a common component of programs designed to prevent ACL injury. Rehabilitation programs can improve postural stability following ACL injury and reconstruction; however, there is limited information available which quantifies improvement of postural stability following neuromuscular training designed to prevent ACL injuries in a healthy population.
Methods and Measures: Forty-one healthy female high school athletes (mean age, 15.3 years; age range, 13-17 years) participated in this study. Single-limb postural stability for both lower extremities was assessed with a Biodex Stability System. The neuromuscular training program consisted of three 90-minute training sessions per week for 6 weeks. Following the completion of the training program, each subject was re-evaluated to determine change in total, anterior-posterior, and medial-lateral single-limb stability. Two-way analysis of variance models were used to determine differences between pretraining and posttraining and between limbs.
Results: The subjects showed a significant improvement in single-limb total stability ($P = .004$) and anterior-posterior stability ($P = .001$), but not medial-lateral stability ($P = .650$) for both the right and left lower extremity following training. In addition, the subjects demonstrated significantly better total postural stability on the right side as compared to the left ($P = .026$).
Conclusions: A 6-week neuromuscular training program designed to decrease the incidence of ACL injuries improves objective measures of total and anterior-posterior single-limb postural stability in high school female athletes. *J Orthop Sports Phys Ther 2004;34:305-316.*

Key Words: *anterior cruciate ligament, balance, knee, prevention, proprioception*

Female athletes injure their anterior cruciate ligaments (ACLs) at a rate 4 to 6 times higher than that of male athletes participating in the same jumping and pivoting sports.[7,10,23,25,34,47] Consequently, there is currently an increased emphasis in sports medicine on the development of training programs designed to decrease the incidence of noncontact ACL injury in female athletes.[5,6,17,21] In addition to reducing the incidence of ACL injuries,[6,17,21,23] these programs have been shown to also improve lower extremity biomechanics during athletic tasks, while increasing athletic performance.[23]

Injury prevention training programs typically incorporate some combination of strengthening, flexibility, plyometrics, and balance components; however, what has not been fully determined is the mechanism of how these programs effectively reduce ACL injuries.[5,6,17,21,23,32,45] Caraffa et al[6] utilized balance board training and noted a 7-fold decrease in ACL injuries in male soccer players.

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Wedderkopp et al[45] instituted an injury prevention program focusing on ankle disc training in young female handball players and compared injury rates of the trained group to a control group. The authors determined that the trained group experienced 79% fewer lower extremity injuries (including sprains, strains, and subluxations) than the control group over one 10-month competitive season. Hewett et al[21] incorporated flexibility, strength training, plyometrics, and several single-leg balance drills in the overall training of female volleyball, basketball, and soccer players. They noted a 72% decrease in major knee injuries in the trained group. While differences exist among these training programs, the 1 common component shared among protocols is the utilization of some form of balance and proprioception exercise.

Balance training has been defined as exercises designed to focus on postural awareness and equilibrium maintenance without changing the base of support[37] and has been incorporated into a variety of training programs. There is a general consensus in the scientific community that balance training can improve postural stability, or the ability to maintain an upright posture under dynamic conditions, in a population with lower extremity injury such as an ACL tear.[2,11,13,39,46] However, this has not been verified in populations with mechanically stable knees.

Stabilometry is an objective and quantitative method for evaluating postural stability.[14,16,35,43] In the past, stabilometry studies were performed on a static force plate with measurement of center of pressure displacement in the sagittal and coronal planes. More recently, dynamic mobile platforms that also measure center of pressure displacement in 2 dimensions have been developed. These measures of stability can be reported as total stability, stability in the anterior-posterior (AP) direction, and stability in the medial-lateral (ML) direction. Arnold et al[3] studied an uninjured population of male and female athletes utilizing the Biodex Stability System (Biodex Corp., Shirley, NY) and determined that there is a close relationship between total stability and AP stability, but not between total stability and ML stability. The authors concluded that there is a need for individual evaluation of each component of postural stability to determine deficits in each plane.

Two recent studies[12,33] have evaluated gender differences in lower extremity kinematics with athletic tasks such as a jumping, landing, and cutting maneuvers, and have found significant differences in coronal plane motion between uninjured male and female athletes. Based on these results, the authors hypothesized that this difference in coronal plane movement may be a risk factor for ACL injury. If there are differences in coronal plane kinematics that increase risk of ACL injury and assessment of total stability is not an accurate indicator of coronal plane stability, then there is a need to individually evaluate both AP and ML stability following a training program designed to decrease ACL injury risk to determine changes that occur in each plane.

Several studies have utilized stabilometry to evaluate subjects following lower extremity injury in an attempt to quantify deficits in stability or ability to regain dynamic joint control after rehabilitation.[8,20,22,35,43,45] Assessment of change in postural stability and proprioceptive ability in these populations was quantified through the assessment of joint position sense, joint kinesthesia, and stabilometry, and has supported the role of postural stability training in the functional stability of the lower extremity following injury.[1,2,13,31,32,38,39]

With respect to patients with mechanically stable knees following ACL reconstruction, proprioception and postural stability can improve over the first 9 to 12 months postoperatively as a result of rehabilitation focused on balance and proprioception.[9,16,20,22,42] Therefore, published evidence demonstrates that rehabilitation with balance, proprioception, and agility training can restore dynamic functional stability in individuals with an ACL-reconstructed knee.

In contrast to the large amount of literature on the effects of neuromuscular rehabilitation focused on balance and proprioception in patients, there is little published data that demonstrate the potential to improve proprioception and postural stability in a healthy, athletic population.[36] Heitkamp et al[18] attempted to determine if short-term balance training alone could improve strength. In doing so, the authors reported that improvements in balance and stabilometry were observed following a 6-week training program. In addition, at least 2 studies have confirmed superior proprioception in athletes participating in sports that require superior balance, such as gymnastics.[30,44] The gymnasts studied either possessed inherent superior balance or developed it following a career of balance training specific to the sport. However, no study to date has quantitatively evaluated the effects of a short-term neuromuscular training program on measures of balance and proprioception and no study has attempted to determine if improvements in postural stability occur following a dynamic, multicomponent program designed to decrease ACL injuries. In addition, it is unknown if improvement in postural stability is the mechanism by which neuromuscular training programs may decrease the risk of ACL injuries in these athletes.

Lloyd[32] suggests that cocontraction of the lower extremity musculature may be responsible for the increased joint stability in the knee during athletic maneuvers and may be a mechanism by which training programs help to decrease knee injury. This author also states that balance and stability training may help to improve the athlete's ability to cocontract lower extremity musculature and ultimately improve lower extremity stability. However, Lloyd[32] notes that no study to date has evaluated how balance and stability training have actually reduced the rate of ACL injury.

The purpose of this study was to determine if a 6-week, multicomponent neuromuscular training program designed to help decrease the incidence of ACL injuries in young female athletes improves single-limb postural stability. Our hypothesis was that, following a 6-week neuromuscular training program, we would see an objective improvement in postural stability as demonstrated by total stability on the Biodex Stability System. In addition, we hypothesized that greater improvement would be reported in the ML direction as compared to the AP direction.

METHODS

Subjects

Fifty-three female athletes from a local high school registered to participate in this study. We established an inclusionary compliance criterion mandating that each participant be present for at least two-thirds (12 of 18) of the training sessions for their data to be included in the results of the study. This criterion allows for an average minimum compliance of 2 sessions per week and has previously been documented in the literature.[21] Forty-one female athletes (77%) met the compliance requirement. These subjects attended a mean of 15 training sessions (±1.67). Twelve of the original 53 subjects (23%) were unable to complete the mandatory amount of training sessions due to conflicting obligations.

The mean age of the 41 subjects was 15.3 years (range, 13-17 years). Ten athletes reported basketball, 15 reported soccer, and 16 reported volleyball as their primary sport. Forty (97.6 %) of 41 subjects had greater than 4 years of participation in their sport and 73.1% had greater than 6 years experience in their respective sport. One participant had 2 years experience in her sport. All training occurred in the summer, immediately prior to the soccer and volleyball seasons, so no organized team sport participation was occurring at the time of training; however, independent athlete participation in sport was not monitored or controlled.

Height and mass were assessed at the pretraining and posttraining test date. Parents or guardians signed informed consent prior to participation in the study. The testing protocol was approved by the Cincinnati Children's Hospital Medical Center Institutional Review Board.

Assessment

Prior to initiating training, single-limb postural stability was assessed on a Biodex Stability System (Biodex, Shirley, NY). The Biodex Stability system is a multiaxial tilting platform that allows the examiner to objectively measure the ability of a subject to maintain dynamic single-limb postural stance on an unstable platform through the use of stabilometry.[3,41] This stabilometric technique allowed assessment of total single-limb postural stability in addition to AP stability, and ML stability. The stability platform allows for varying levels of difficulty of stability testing, ranging from level 8 (most stable) to level 1 (least stable). Schmitz et al[41] examined the intrarater reliability of the Biodex Stability System and reported an intraclass correlation coefficient (ICC) value of 0.82 for total stability, using a descending stability test from level 8 to level 2 over a 30-second trial. Hinman et al[24] reported intratester reliability of 0.89 at level 3 based on 2 separate 30-second trials. Initial between-session reliability data collected in our lab on 5 female athletes (mean age, 16.9 ± 5.0 years) on 3 separate days at level 4 resulted in $ICC_{3,1}$ values of 0.72 for total stability, 0.77 for AP stability, and 0.81 for ML stability.

FIGURE 1. Assessment of single-limb postural stability utilizing the Biodex Stability System.

Prior to testing, the subject was asked to center the foot on the platform in a position that was level and stable. This foot placement was maintained throughout all 3 trials for the test leg. This position was used as the level reference point from which degree of displacement was measured. The subject was instructed to stand on 1 foot with the knee slightly flexed on the free-moving stability platform, with the contralateral knee flexed to 90° for 20 seconds (Figure 1). The subject was then instructed to keep the platform as stable as possible. After reviewing the current literature regarding reliability,[24,41] and considering the authors' own personal experience with testing on the Biodex Stability System, level 4 was selected for use during testing. The authors theorized that in addition to having lower reliability, level 2 would be too unstable for some participants. Conversely, levels 6 through 8 had superior reliability, but may not be sufficiently challenging to allow subtle differences in stability in athletic populations to be observed. Therefore, level 4 was utilized for all testing. The subjects were instructed to cross their arms at their chest to minimize their use in attaining balance, as per system operation procedures.[4] No verbal feedback was given during the testing and while the subjects kept their eyes open, they were allowed no visual feedback regarding their performance during the test, as the control screen was covered during all testing. The Stability System was positioned facing the corner of the room and each subject was asked to look straight ahead and focus on a point on the wall in front of the subject. Each leg was tested 3 times, as done in previous studies utilizing the Stability System for an assessment of postural stability.[40,41] The mean displacement from the referenced, level position during the 20-second trial was calculated for each trial.

The mean and standard deviation of the 3 trials was calculated by the Stability System. The data were analyzed and reported as total stability index, AP stability index, and ML stability index, which is the mean displacement of the platform in degrees, from a level position. A higher stability index from the reference point indicates a greater difficulty of the subject to maintain the platform in a stable position. This indicates less postural stability demonstrated by the subject. Conversely, the lower the stability index, the more stable the platform, representing greater postural stability of the subject.

Training

The training program utilized in this study was a synthesis of exercises used in published research studies[6,15,17,19,21,23,26-29] and prevention techniques developed through recent empirical and analytical evaluations of neuromuscular training programs. The 3 components of the dynamic neuromuscular training protocol utilized in this study include: (1) balance training and hip/pelvis/trunk strengthening, (2) plyometrics and dynamic movement training, and (3) resistance training. Each training component focused on regular instruction regarding appropriate technique from the instructor with continuous feedback to the athlete both during and following training.

General Guidelines to Training The training protocol stressed technique perfection for each exercise, especially in the early training sessions. Each session maintained a 1:4 instructor-participant ratio and was directed by a certified strength and conditioning specialist. The trainers were skilled in recognizing the desired technique for a given exercise and consistently encouraged the athlete to maintain proper technique performance for as long as possible. When the athlete fatigued to a point that she could not perform the exercise with near perfect technique, the exercise was stopped. The athlete recorded the duration of the exercises and number of repetitions completed. The goal of the next training session was to continue to improve technique, while increasing duration, volume, or intensity of the exercise. In addition to technique perfection, the neuromuscular training was progressed to ensure a continued challenge to the athlete and maximize potential for successful outcomes (Table and Appendix A). The neuromuscular training stressed performance of general athletic maneuvers in a powerful, efficient, and safe manner.

TABLE. Sample exercise progressions from the balance and hip/pelvis/trunk strengthening protocol.

Initial Phase (Weeks 1-2)	Intermediate Phase (Weeks 3-4)	Late Phase (Weeks 5-6)
Stable surface progression		
Broad jump, stick landing	Single-leg, stick landing	Single-leg crossover, stick landing
Box drop, stick landing	Box drop medicine ball catch	Box drop 180° medicine ball catch
Unstable surface (BOSU) progression		
Double-leg balance (Figure 3)	Single-leg balance	Single-leg balance (perturbation/sport)
Double-knee balance	Single-knee balance (Figure 2)	Hip-side balance
Targeted hip/pelvis/trunk strengthening		
Abdominal crunch	BOSU abdominal crunch	BOSU abdominal V-sit/toe touch
Lower back superman's	BOSU lower back superman's	Back hyperextensions

The athletes participated in the training program 3 days per week with at least 1 day of rest between each session. Each training session lasted for 90 minutes and began with an active warm-up that included jogging, backwards running, lateral shuffling, and carioca. During each training session, the athlete participated in 2 of the 3 components of the program, resulting in 2 exposures per week to each component of the program. At the end of each training session the athletes performed self-selected stretching exercises for 15 minutes. This cycle of training was repeated each week for the training period of 6 weeks.

Balance Training and Hip/Pelvis/Trunk Strengthening The balance training and hip/pelvis/trunk strengthening component of the protocol followed an organized exercise selection specifically directed at strengthening the hip/pelvis/trunk stabilizing muscles. The training was structured to provide the appropriate intensity and progression of exercises. The training progression took the athlete through a combination of low- to higher-intensity maneuvers in a controlled situation (Table). The goal of the functional balance training and hip/pelvis/trunk strengthening was to improve hip/pelvis/trunk stability and coordination in an attempt to properly control force, maintain balance and posture, and subsequently regenerate force in the desired direction. The athletes did not train or practice on the Biodex Stability System.

The initial phase of the balance training and hip/pelvis/trunk strengthening component lasted 2 weeks and focused on development of baseline stability and good technique (Table). Early balance exercises included double-limb jumping activities with a focus on correct landing posture, which has been described by previous authors.[21,23] In addition, low-intensity single-leg hops were introduced at this time, again with a focus on maintaining balanced landing. During the beginning stages, progressions were made from decreasing frequency of double-limb jumps and increasing frequency of single-limb hops. Balance on an unstable surface was also introduced using bilateral stance exercises on the ''both sides up'' (BOSU) balance device (DW Fitness, LLC, Madison, NJ). The BOSU (Figures 2 and 3) is a balance device with a circular platform on 1 side and an inflated half-sphere on the opposite side. It provides an unstable platform to further challenge the subject's balance and stability. The initial stages of training also included a component that focused on abdominal, mid-back, low-back, and hip strengthening.

The intermediate phase of the balance training and hip/pelvis/trunk strengthening portion of the neuromuscular training program occurred during the third and fourth week of training. During this time the athlete was progressed to more single-limb stance movements with a decrease in volume of double-limb stance on stable surfaces. In addition, stable surface activities progressed into more multiple-plane movements. Trunk strengthening was also progressed during this phase to knee support balance drills (Figure 2) and unanticipated perturbations.

FIGURE 2. Example of hip/pelvis/trunk training with single-knee stance on unstable surface.

The late phase of the balance training and hip/pelvis/trunk strengthening exercises lasted 2 weeks and focused on training on an unstable surface with single-limb support. The training included static holds with upper extremity involvement, as well as dynamic activities such as jumping onto and off the unstable surface in multiple planes and rotational jumps on the unstable platform. Hip/pelvis/trunk strengthening was also continued with abdominal and trunk strengthening activities. The focus of the late stage was to develop stability in a single-limb stance position in unstable and unanticipated environments, with the goal of preparing the athlete to react appropriately in an athletic situation. Ultimately, the goal is to provide stability and avoid injury. Figure 3 demonstrates a typical exercise progression during the balance training.

Plyometrics and Dynamic Movement Training The plyometrics and dynamic movement training component emphasized a progression of jumping, pivoting, and cutting maneuvers from double-limb to single-limb movements throughout the training phases.

Resistance Training The resistance-training component of the protocol was periodized with an initial high-volume, low-intensity protocol. The goal of the resistance training component of the protocol was to strengthen all major muscle groups through complete range of motion and to provide complementary muscular strength and power to the plyometric and balance components of the protocol. Appendix A describes the specific exercises executed during each phase of training.

FIGURE 3. Demonstration of balance training exercise progression on unstable platform (BOSU) from double-limb stance to single-limb stance to double-limb stance with perturbation to single-limb stance with sports-specific perturbation.

Data Analysis

Mean and SD of height and mass were reported for all subjects pretraining and posttraining. A paired *t* test was used to determine significant changes in these variables ($P<.05$).

For assessment of postural stability, mean and SD of postural stability of the 3 single-limb trials for both legs of each subject was recorded at the pretraining and the posttraining sessions for total stability, AP stability, and ML stability. The group mean and SD for each leg pretraining and posttraining were calculated for descriptive purposes. Three separate 2 × 2 (side × training) repeated-measures 2-way analyses of variance (ANOVAs) were conducted to determine if any difference existed between sides (right versus left) and time of testing (pretraining versus posttraining) for total stability, AP stability, and ML stability. A Pearson correlation coefficient was measured to determine the degree of association between total stability and AP and ML stability. Significance was set at $P<.05$. Statistical analyses were conducted in SPSS for Windows, Release 10.0.7 (SPSS, Inc., Chicago, IL).

RESULTS

Height and mass of the subjects were evaluated pretraining and posttraining. The initial height (mean ± SD) of the participants was 171.2 ± 7.2 cm, and mass (mean ± SD) was 64.8 ± 10.0 kg. Assessment of height and mass after 6 weeks of training revealed no change in mean height; however, a very small but statistically significant increase in mass (65.7 ± 6.7 kg) was noted ($P = .001$).

Mean and SD of single-limb postural stability pretraining and posttraining for total stability, AP stability, and ML stability are reported in Figures 4, 5, and 6 for the right and left lower extremities. The results of the ANOVA for total stability indicated a main effect for training ($F_{1,40} = 9.4$, $P = .004$), and for side ($F_{1,40} = 5.4$, $P = .026$), with stability posttraining being better than pretraining and stability on the right side being better than stability on the left side. There was no interaction between the variables of side and training ($P = .674$).

The results of the ANOVA indicated a significant training main effect for AP stability ($F_{1,40} = 11.7$, $P = .001$), with posttraining values being better than the pretraining values (Figure 5). There was no significant difference for AP stability between the right and left lower extremity ($F_{1,40} = 3.1$, $P = .086$). There was also no significant interaction between the variables of side and training ($P = .866$).

No significant difference was found between pretraining and posttraining ($F_{1,40} = .2$, $P = .65$) and between lower extremities ($F_{1,40} = 2.5$, $P = .12$) for stability in the ML direction. There was no interaction between the variables of side and training ($P = .835$).

Finally, a strong correlation was observed between total stability index and AP stability index for the right leg ($r = .954$, $P<.001$) and the left leg ($r = .923$,

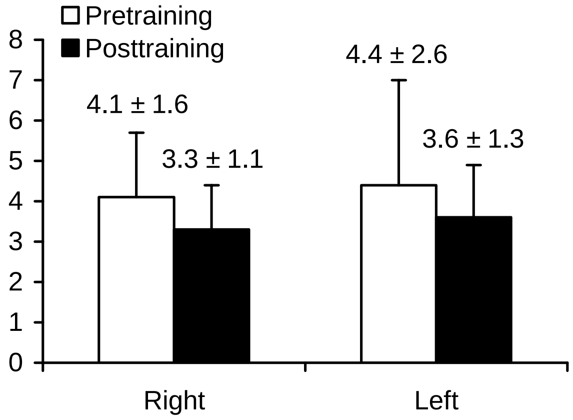

FIGURE 4. Mean total stability index pretraining and posttraining for the right and left lower extremity. Posttraining values are significantly better than pretraining values ($P = .004$) and stability on the right lower extremity is better than on the left side ($P = .026$). The error bars are 1 SD.

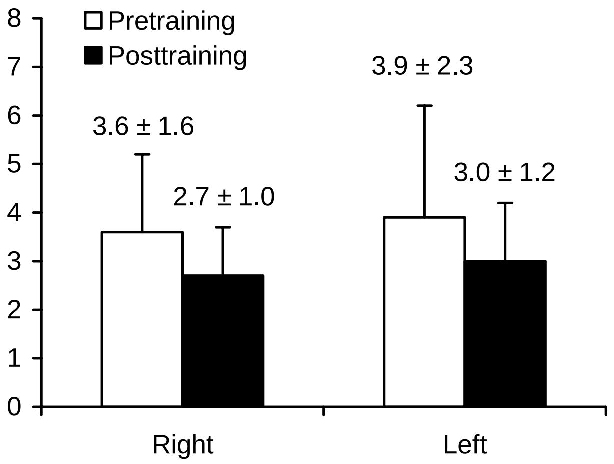

FIGURE 5. Mean anterior-posterior stability index pretraining and posttraining for the right and left lower extremity. Posttraining values are significantly better than pretraining values (P = .001). The bars are 1 SD.

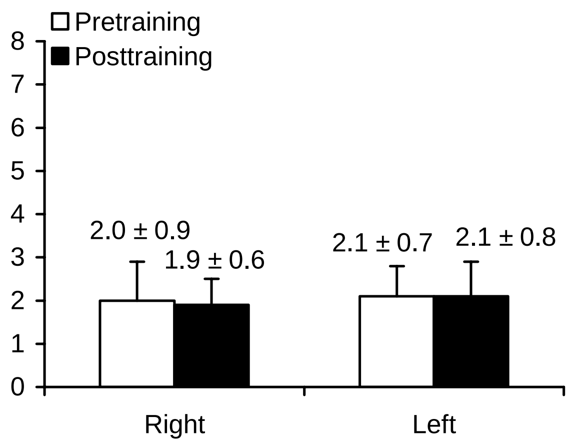

FIGURE 6. Mean medial-lateral stability index pretraining and posttraining for the right and left lower extremity. Medial-lateral stability did not change with training. The bars are 1 SD.

P<.001). There was only a moderate correlation between total stability index and ML stability index for the right leg (r = .601, P<.001) and the left leg (r = .733, P<.001).

DISCUSSION

Participation in a structured 6-week preseason neuromuscular training program designed to decrease ACL injury significantly improved total and AP direction single-limb postural stability measures in young female athletes. However, no change in stability in the ML direction was noted.

In the uninjured population, to our knowledge, the effect of short-term neuromuscular training designed to help decrease knee injuries on postural stability and proprioception has not been reported in the published literature. Two authors have retrospectively evaluated the proprioceptive capacity of gymnasts who participated in long-term proprioceptive training as part of their sport. Lephart et al[30] and Vuillerme et al[44] found that gymnasts were better able to maintain postural stability when compared to nongymnasts. These studies both suggest improvement in proprioceptive ability and postural stability with long-term training; however they did not report the effects on proprioception of a short-term training program. Our findings suggest that in as little as 6 weeks of neuromuscular training there can be a significant improvement in total and AP postural stability in young female athletes.

Similar to the findings of Arnold et al,[3] our results show a strong correlation between total stability index and AP stability index for the right leg (r = 0.954, P<.001) and the left leg (r = .923, P<.001), and only moderate correlation between total stability index and ML stability index for the right leg (r = .601, P<.001) and the left leg (r = .733, P<.001). This finding is, in part, the result of the higher magnitude of motion demonstrated in the AP direction as opposed to the ML direction and is supported by a few studies in the literature.[3,22] These findings further substantiate the need to evaluate total stability and ML stability independent of each another.

With respect to ML movement, Ford et al[12] reported increased valgus knee motion in normal female basketball players when compared to males during a drop jump task. Malinzak et al[33] demonstrated increased knee valgus angles and decreased knee flexion angles in female athletes performing cutting tasks when compared to male controls. These gender differences in coronal plane kinematics in uninjured female athletes may represent an increased risk for ACL injury. Considering these gender differences, we hypothesized that following a training program designed to decrease ACL injury risk, there would be an improvement in coronal plane postural stability. However, our results demonstrated no significant improvement in stability in the ML direction.

A retrospective analysis of our training program design was conducted to determine if any bias existed to explain the significant improvement in AP stability and failure to demonstrate significant improvement in the ML direction. The training program utilized AP perturbations on an unstable platform without ML perturbations and may have failed to properly stimulate stability improvement in the ML direction. Further research is needed to investigate the potential of neuromuscular training focused on improving ML stability, specifically ML perturbations.

With respect to neuromuscular training, there have been a few studies documenting the importance of preseason training programs on the prevention of ACL injuries; however these have failed to investigate the changes in postural stability that may have occurred. Caraffa et al[6] conducted a prospective study of European male soccer players in an attempt to decrease the incidence of ACL injuries. The authors had the study group participate in progressive proprioceptive training that utilized balance board and disk training drills and found a 7-fold decrease in the incidence of ACL injuries when compared to a control group; however, the athlete's improvement in postural stability was not objectively measured. Wedderkopp et al[45] implemented a prospective intervention program designed to decrease injury rate in elite European female handball players. The authors reported an 80% decrease in injuries during games and a 71% decrease in injuries in practice for the intervention group when compared to the control group. Hewett et al[21] reported a 72% decrease in serious knee injuries in female athletes following participation in a 6-week preseason training program including flexibility, strength training, plyometric training, and single-leg balance drills; however, no quantification of improvement in proprioception or postural stability was reported. Thus, it cannot be determined if the mechanism resulting in decrease injury rate was related to improved proprioception and postural stability or other unmeasured variables.

These previously reported findings, coupled with the results of the current study, provide a novel contribution to the scientific literature. Our findings help substantiate that the balance component is improved following preseason training designed to help decrease ACL injuries. In the work of Caraffa et al[6] and Hewett et al,[21] an athletic population is shown to have a marked decrease in noncontact ACL and MCL injury incidence following training. While our findings suggest that participation in such training will aid in the improvement of postural stability that may improve dynamic joint stability in the knee and decrease ACL injuries in female athletes, our study did not look at dynamic joint stability and the incidence of ACL injuries. Therefore, no conclusion can be reached at this time.

Future research should explore the possibility that deficits in total, AP, or ML postural stability may be a risk factor for ACL injury. If this is the case, then assessing postural stability in the preseason may help identify young female athletes who have deficits in postural stability, dynamic joint control at the knee, and ultimately are at higher risk for ACL injury. Identification of a high-risk group is the first step in determining what population of athletes should participate in preseason neuromuscular training to help decrease the incidence of knee injury. Prior studies by Tropp et al[43] demonstrated that an abnormal stabilometric score was predictive of future ankle injury. No study has associated deficits in postural stability to increased incidence of knee injury. Neuromuscular training programs implemented at the team level, such as those demonstrated by Caraffa et al[6] and Hewett et al,[21] appear to be successful at decreasing the incidence of knee injuries, but they have not been effectively targeted towards individuals who may be at the highest risk.

This study has several possible limitations that need to be considered. First, the neuromuscular training we utilized was a multicomponent program including balance training, plyometrics, and resistance training. A single component of this program (ie, balance training) may have been solely responsible for the improvement seen in postural stability; however, we are unable to dissect out the separate effects of each of the components of the program. Secondly, there is a limit to the generalizability of the effects of training because the focus of this study was on young female athletes. The question, however, still remains if males would benefit equally from such a training program. Knowing the biomechanical differences between male and female athletes, it would be inappropriate to assume the same results would occur in male athletes. Thirdly, it is assumed that the improvements in postural stability seen following the 6-week preseason training persist through the season. However, this study is unable to determine if the changes seen at the end of training persisted throughout the season or if they deteriorate over time, because no repeat testing was performed postseason. Finally, there was no control group tested in the study, therefore we are unable to unequivocally determine if the changes noted in postural stability were in fact due to the intervention.

Future studies should attempt to further quantify the presence of other biomechanical and neuromuscular improvements that may be observed following structured preseason neuromuscular training designed to reduce the incidence of ACL injuries in female athletes. Methods to refine programs aimed at effectively reducing the rate of ACL injuries in female athletes need to be determined.

CONCLUSIONS

Single-limb postural stability and proprioception is a key component to the functional status of the lower extremity. This study shows that 6 weeks of neuromuscular training can improve single-limb postural balance as measured by an index of total stability and AP stability, but not ML stability.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. Jeffrey Robbins, Division of Molecular and Cardiovascular Biology, and Rebecca Reder, Division of Occupational Therapy and Physical Therapy, for ongoing support of our work, and Melissa Mays for her assistance in the preparation of this manuscript.

REFERENCES

1. Ageberg E. Consequences of a ligament injury on neuromuscular function and relevance to rehabilitation - using the anterior cruciate ligament-injured knee as model. *J Electromyogr Kinesiol.* 2002;12:205-212.
2. Ageberg E, Zatterstrom R, Moritz U, Friden T. Influence of supervised and nonsupervised training on postural control after an acute anterior cruciate ligament rupture: a three-year longitudinal prospective study. *J Orthop Sports Phys Ther.* 2001;31:632-644.
3. Arnold BL, Schmitz RJ. Examination of balance measures produced by the Biodex Stability System. *J Athl Train.* 1998;33:323-327.
4. Biodex System Operation and Service Manual (#945-300). Shirley, NY: Biodex Medical Systems, Inc.; 2002.
5. Cahill BR, Griffith EH. Effect of preseason conditioning on the incidence and severity of high school football knee injuries. *Am J Sports Med.* 1978;6:180-184.
6. Caraffa A, Cerulli G, Projetti M, Aisa G, Rizzo A. Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc.* 1996;4:19-21.
7. Chandy TA, Grana WA. Secondary school athletic injury in boys and girls: A three-year comparison. *Phys Sportsmed.* 1985;13:106-111.
8. Co FH, Skinner HB, Cannon WD. Effect of reconstruction of the anterior cruciate ligament on proprioception of the knee and the heel strike transient. *J Orthop Res.* 1993;11:696-704.
9. Denti M, Randelli P, Lo Vetere D, Moioli M, Bagnoli I, Cawley PW. Motor control performance in the lower extremity: normals vs. anterior cruciate ligament reconstructed knees 5-8 years from the index surgery. *Knee Surg Sports Traumatol Arthrosc.* 2000;8:296-300.
10. Ferretti A, Papandrea P, Conteduca F, Mariani PP. Knee ligament injuries in volleyball players. *Am J Sports Med.* 1992;20:203-207.
11. Fitzgerald GK, Axe MJ, Snyder-Mackler L. The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. *Phys Ther.* 2000;80:128-140.
12. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* 2003;35:1745-1750.
13. Friden T, Roberts D, Ageberg E, Walden M, Zatterstrom R. Review of knee proprioception and the relation to extremity function after an anterior cruciate ligament rupture. *J Orthop Sports Phys Ther.* 2001;31:567-576.
14. Friden T, Zatterstrom R, Lindstrand A, Moritz U. A stabilometric technique for evaluation of lower limb instabilities. *Am J Sports Med.* 1989;17:118-122.
15. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* 2000;8:141-150.
16. Harrison EL, Duenkel N, Dunlop R, Russell G. Evaluation of single-leg standing following anterior cruciate ligament surgery and rehabilitation. *Phys Ther.* 1994;74:245-252.
17. Heidt RS, Jr., Sweeterman LM, Carlonas RL, Traub JA, Tekulve FX. Avoidance of soccer injuries with preseason conditioning. *Am J Sports Med.* 2000;28:659-662.
18. Heitkamp HC, Horstmann T, Mayer F, Weller J, Dickhuth HH. Gain in strength and muscular balance after balance training. *Int J Sports Med.* 2001;22:285-290.
19. Hejna W, Rosenberg A, Buturusis D, Krieger A. The prevention of sports injuries in high school students through strength training. *Nat Strength Coaches Assoc J.* 1982;4:23-31.
20. Henriksson M, Ledin T, Good L. Postural control after anterior cruciate ligament reconstruction and functional rehabilitation. *Am J Sports Med.* 2001;29:359-366.
21. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med.* 1999;27:699-706.
22. Hewett TE, Paterno MV, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop.* 2002;76-94.
23. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med. 1996;24:765-773.*
24. Hinman MR. Factors affecting reliability of the Biodex Balance System: a summary of four studies. *J Sport Rehabil.* 2000;9:240-252.
25. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996;24:427-436.
26. Kraemer WJ. A series of studies: the physiological basis for strength training in American football: fact over philosophy. *J Strength Cond Res.* 1997;11:131-142.
27. Kraemer WJ, Duncan ND, Volek JS. Resistance training and elite athletes: adaptations and program considerations. *J Orthop Sports Phys Ther.* 1998;28:110-119.
28. Kraemer WJ, Hakkinen K, Triplett-Mcbride NT, et al. Physiological changes with periodized resistance training in women tennis players. *Med Sci Sports Exerc.* 2003;35:157-168.
29. Lehnhard RA, Lehnhard HR, Young R, Butterfield SA. Monitoring injuries on a college soccer team: the effect of strength training. *J Strength Cond Res.* 1996;10:115-119.
30. Lephart SM, Giraldo JL, Borsa PA, Fu FH. Knee joint proprioception: a comparison between female intercollegiate gymnasts and controls. *Knee Surg Sports Traumatol Arthrosc.* 1996;4:121-124.
31. Lephart SM, Pincivero DM, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med.* 1997;25:130-137.
32. Lloyd DG. Rationale for training programs to reduce anterior cruciate ligament injuries in Australian football. *J Orthop Sports Phys Ther.* 2001;31:645-654; discussion 661.
33. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon).* 2001;16:438-445.
34. Malone TR, Hardaker WT, Garrett WE, Feagin JA, Bassett FH. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *J South Orthop Assoc.* 1993;2:36-39.
35. Mizuta H, Shiraishi M, Kubota K, Kai K, Takagi K. A stabilometric technique for evaluation of functional instability in anterior cruciate ligament-deficient knee. *Clin J Sport Med.* 1992;2:235-239.
36. Orchard J, Seward H, McGivern J, Hood S. Intrinsic and extrinsic risk factors for anterior cruciate ligament injury in Australian footballers. *Am J Sports Med.* 2001;29:196-200.
37. Risberg MA, Mork M, Jenssen HK, Holm I. Design and implementation of a neuromuscular training program following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2001;31:620-631.

38. Roberts D, Friden T, Stomberg A, Lindstrand A, Moritz U. Bilateral proprioceptive defects in patients with a unilateral anterior cruciate ligament reconstruction: a comparison between patients and healthy individuals. *J Orthop Res.* 2000;18:565-571.
39. Roberts D, Friden T, Zatterstrom R, Lindstrand A, Moritz U. Proprioception in people with anterior cruciate ligament-deficient knees: comparison of symptomatic and asymptomatic patients. *J Orthop Sports Phys Ther.* 1999;29:587-594.
40. Rozzi SL, Lephart SM, Gear WS, Fu FH. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *Am J Sports Med.* 1999;27:312-319.
41. Schmitz R, Arnold B. Intertester and intratester reliability of a dynamicbalance protocol using the Biodex Stability System. *J Sport Rehabil.* 1998;7:95-101.
42. Shiraishi M, Mizuta H, Kubota K, Otsuka Y, Nagamoto N, Takagi K. Stabilometric assessment in the anterior cruciate ligament-reconstructed knee. *Clin J Sport Med.* 1996;6:32-39.
43. Tropp H, Ekstrand J, Gillquist J. Factors affecting stabilometry recordings of single limb stance. *Am J Sports Med.* 1984;12:185-188.
44. Vuillerme N, Danion F, Marin L, et al. The effect of expertise in gymnastics on postural control. *Neurosci Lett.* 2001;303:83-86.
45. Wedderkopp N, Kaltoft M, Lundgaard B, Rosendahl M, Froberg K. Prevention of injuries in young female players in European team handball. A prospective intervention study. *Scand J Med Sci Sports.* 1999;9:41-47.
46. Zatterstrom R, Friden T, Lindstrand A, Moritz U. The effect of physiotherapy on standing balance in chronic anterior cruciate ligament insufficiency. *Am J Sports Med.* 1994;22:531-536.
47. Zelisko JA, Noble HB, Porter M. A comparison of men's and women's professional basketball injuries. *Am J Sports Med.* 1982;10:297-299.

Appendix

Athletes completed 2 sessions from each of the 3 protocol sections (hip/pelvis/trunk strengthening and balance training, plyometrics and dynamic movement training, and resistance training) each week during the 6-week training program. (Abbreviations: r, recommended exercise repetitions; s, recommended exercise time [seconds]).

Section 1: Hip/pelvis/trunk strengthening and balance training sessions.

	Training Sessions											
Exercises	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
BOSU superman (right-left)	1 × 15 r	1 × 17 r	1 × 17 r	1 × 15 r	1 × 20 r	1 × 20 r	1 × 20 r	1 × 20 r	2 × 25 r	2 × 25 r	2 × 25 r	2 × 25 r
BOSU crunches	2 × 35 r	2 × 40 r	2 × 40 r	2 × 35 r	1 × 55 r	1 × 55 r	1 × 55 r	1 × 55 r				
BOSU double-leg perturbations	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s				
BOSU double-leg pick	1 × 10 r	1 × 10 r	1 × 10 r	1 × 10 r	1 × 10 r	1 × 10 r	1 × 10 r	1 × 10 r				
Broad jump-stick landing	1 × 8 r	1 × 8 r	1 × 8 r	1 × 8 r	1 × 4 r	1 × 4 r	1 × 4 r	1 × 4 r				
Single-leg × hop (right-left)	1 × 3 r	1 × 4 r	1 × 4 r	1 × 3 r	1 × 5 r	1 × 5 r	1 × 5 r	1 × 5 r				
180° jumps stick landing	1 × 10 r	1 × 10 r	1 × 10 r	1 × 10 r								
BOSU both knees deep hold	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s								
BOSU both legs deep hold	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s								
BOSU jump stick landing	1 × 8 r	1 × 8 r	1 × 8 r	1 × 8 r								
BOSU swivel crunch (feet planted)	2 × 40 r	2 × 40 r	2 × 40 r	2 × 40 r								
Box drop stick landing	1 × 8 r	1 × 8 r	1 × 8 r	1 × 8 r								
Hop-stick landing (right-left)	1 × 5 r	1 × 5 r	1 × 5 r	1 × 5 r	1 × 6 r							
BOSU single-leg deep hold					2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s
BOSU V-sit toe touches					1 × 15 r	1 × 15 r	1 × 15 r	1 × 15 r	1 × 15 r	1 × 15 r	1 × 15 r	1 × 15 r
Double crunch					2 × 25 r	2 × 25 r	2 × 25 r	2 × 25 r	1 × 25 r	1 × 25 r		
180° jumps stick landing, medicine ball catch					1 × 6 r	1 × 6 r	1 × 6 r	1 × 6 r				
BOSU both knees deep hold, medicine ball catch					2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s				
BOSU swivel crunch (feet up)					2 × 30 r	2 × 30 r	2 × 30 r	2 × 30 r				
Box drop medicine ball catch					1 × 8 r	1 × 8 r	1 × 8 r	1 × 8 r				
Crossover hop-stick						1 × 12 r	1 × 12 r	1 × 12 r	1 × 12 r	1 × 12 r	1 × 12 r	1 × 12 r
BOSU 180° jumps stick landing									1 × 15 r	1 × 15 r	1 × 15 r	1 × 15 r
BOSU jump stick landing, medicine ball catch									1 × 8 r	1 × 8 r	1 × 8 r	1 × 8 r
BOSU partner toss (feet up)									2 × 30 s	2 × 30 s	2 × 30 s	2 × 30 s
BOSU single-knee deep hold									2 × 20 s	2 × 20 s	2 × 20 s	2 × 20 s
BOSU single-leg deep hold, multiple switches									2 × 30 s	2 × 30 s	2 × 30 s	2 × 30 s
BOSU single-leg pick (right-left)									1 × 8 r	1 × 8 r	1 × 8 r	1 × 8 r
BOSU double crunch											1 × 25 r	2 × 25 r
BOSU hop stick landing (right-left)											1 × 8 r	1 × 8 r
BOSU opposite knee to elbow											1 × 25 r	2 × 25 r

Section 2. Plyometrics and dynamic movement training.

	Training Sessions											
Exercises	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Wall jumps (ankle bounces)	1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s
Squat jumps	1 × 10 s	2 × 15 s	1 × 15 s	2 × 15 s	1 × 15 s	1 × 15 s	1 × 10 s	1 × 10 s	1 × 10 s	1 × 10 s		
180° jumps (height)	1 × 15 s				1 × 15 s			1 × 15 s			1 × 15 s	
Barrier jumps (side to side)	1 × 10 s	1 × 10 s		1 × 10 s	1 × 10 s							
Bounding in place	1 × 20 s	1 × 20 s										
Box depth max vertical	1 × 10 r	1 × 10 r										
Box depth reaction	1 × 10 r	1 × 10 r										
Broad jump vertical	1 × 10 r	1 × 10 r										
Forward barrier hops with middle box	1 × 6 r	1 × 6 r										
Forward hops over barriers	1 × 6 r	1 × 6 r										
Lunge jump	2 × 10 s	2 × 10 s										
Tuck jump (with thighs parallel)	2 × 10 s	1 × 10 s	1 × 10 s	1 × 10 s								
180° jumps (speed)		1 × 15 s		2 × 15 s			1 × 15 s			1 × 15 s		1 × 15 s
Backward-forward box depth max vertical			1 × 10 r	1 × 10 r	1 × 10 r	1 × 10 r						
Barrier jumps (front to back)			1 × 15 s	1 × 15 s	1 × 15 s	1 × 15 s						

Section 2. Plyometrics and dynamic movement training. (cont'd)

Exercises	Training Sessions											
	1	2	3	4	5	6	7	8	9	10	11	12
Bounding for distance			1 × 6 r	1 × 6 r	1 × 6 r	1 × 6 r						
Scissors jump			1 × 10 s	1 × 10 s								
Tuck jump (with butt kick)			2 × 10 s	1 × 10 s	1 × 10 s	1 × 10 s						
180° jumps, broad jump			2 × 15 s			1 × 15 s			1 × 15 s			
Forward barrier hops with staggered box			1 × 6 r	1 × 6 r			1 × 6 r	1 × 6 r				
Box depth max, vertical, reaction			1 × 10 r	1 × 10 r								
Broad jump, jump, vertical			1 × 10 r	1 × 10 r								
Zig-zag jumps over barriers			1 × 6 r	1 × 6 r								
Broad jump, jump, jump, vertical					1 × 10 r	1 × 10 r	1 × 6 r	1 × 6 r	1 × 6 r	1 × 6 r		
Hop, hop, hop-stick (right-left)					1 × 6 r	1 × 6 r	1 × 6 r	1 × 6 r				
Lateral barrier hops					1 × 6 r	1 × 6 r						
Lateral barrier hops with staggered box					1 × 6 r	1 × 6 r	1 × 6 r	1 × 6 r				
Power steps (right-left)					1 × 10 r	1 × 10 r						
Tuck jump (with abdominal crunch)					2 × 5 s	1 × 15 s	1 × 10 s	1 × 10 s	1 × 10 s	1 × 10 s		
Barrier jumps (front-to-back) speed							1 × 15 s	1 × 15 s				
Barrier jumps (side-to-side) speed							1 × 15 s	1 × 15 s				
BOSU 180° jumps stick landing							1 × 15 r	1 × 15 r				
Box depth 180°, box depth max, vertical							1 × 8 r	1 × 8 r	1 × 8 r	1 × 8 r		
Jump into bounding							1 × 6 r	1 × 6 r				
3 barrier hop, reaction (3-way)									1 × 9 r	1 × 9 r	1 × 9 r	1 × 9 r
Barrier hops flat (front-to-back) (right-left)									1 × 12 s	1 × 12 s	1 × 12 s	1 × 12 s
Barrier hops flat (side-to-side) (right-left)									1 × 12 s	1 × 12 s	1 × 12 s	1 × 12 s
Box depth, broad jump									1 × 8 r	1 × 8 r		
Crossover hop, hop, hop-stick (width)									1 × 10 r		1 × 10 r	
Multidirectional barrier hops									1 × 6 r	1 × 6 r		
Crossover hop, hop, hop-stick (distance)										1 × 10 r		1 × 10 r
Box depth, 180°, box depth, vertical, reaction											1 × 8 r	1 × 8 r
Box depth-180°-reaction											1 × 8 r	1 × 8 r
Broad jump, jump, jump, vertical, reaction											1 × 6 r	1 × 6 r
Forward/backward hops over barrier											1 × 6 r	1 × 6 r
Squat-tuck jumps											1 × 12 s	1 × 12 s

Section 3. Resistance training (sets × repetitions).

Exercises	Training Sessions											
	1	2	3	4	5	6	7	8	9	10	11	12
Lateral pulldown	2 × 12	2 × 12	2 × 12	2 × 12	2 × 10	2 × 10	2 × 8	2 × 8	1 × 8	1 × 8		1 × 8
Ankle, plantar-dorsi	1 × 12		1 × 12		1 × 12		1 × 12		1 × 12	1 × 12	1 × 12	1 × 12
Benchpress	2 × 12		2 × 12		2 × 12		2 × 12		3 × 12	3 × 12		3 × 12
Db hang snatch	2 × 12		2 × 12		2 × 10		2 × 8		2 × 8	2 × 5		3 × 5
Leg curl	2 × 12		2 × 12		2 × 10		2 × 8		3 × 8	3 × 5		3 × 5
Shoulder press	2 × 12		2 × 12		2 × 10		2 × 8		1 × 8	1 × 8		1 × 8
Squat	2 × 12		2 × 12		2 × 10		2 × 8		3 × 8	3 × 5		3 × 5
Back fly	2 × 12		2 × 12		2 × 12		2 × 12				1 × 12	
Bicep circuit	1 × 12		1 × 12		1 × 12		1 × 12				1 × 12	
Russian good mornings	2 × 12		2 × 12		2 × 12		2 × 15				1 × 15	
Ankle, eversion-inversion		1 × 12		1 × 12		1 × 12		1 × 12				
Cable rows		2 × 12		2 × 12		2 × 12		2 × 12				
Db incline		2 × 12		2 × 12		2 × 10		2 × 8			2 × 8	
Hang cleans		2 × 12		2 × 12		2 × 10		2 × 8			2 × 8	
Leg press		2 × 12		2 × 12		2 × 10		2 × 8			2 × 8	
Lunge circuit		1 × 12		1 × 12		2 × 10		1 × 8			1 × 8	
Shoulder circuit		1 × 12		1 × 12		1 × 10		1 × 8			1 × 8	
Straight-leg dead lift		2 × 12		2 × 12		2 × 12		2 × 12				
Tricep circuit		1 × 12		1 × 12		1 × 12		1 × 12				