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Article Title: The Protective Effect of Neuromuscular Training on the Medial Tibial Stress Syndrome in Youth Female Track and Field Athletes: A Clinical Trial and Cohort Study

Running head: Neuromuscular Training and Injury in Athletes

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The Protective Effect of Neuromuscular Training on the Medial Tibial Stress Syndrome in Youth Female Track and Field Athletes: A Clinical Trial and Cohort Study

Abstract

Context: Few reports have analyzed the effects of neuromuscular (NM) training programs on the injury incidence among youth female track and field athletes.

Objective: To determine the effects of a NM training on reducing lower limb injury incidence and to establish its effects on countermovement jump (CMJ) performance, balance, 30-m sprint and joint position sense in youth female track and field athletes.

Design: Single-blind, randomized-controlled clinical trial.

Setting: Sports research laboratory.

Participants: Twenty-two female athletes were allocated into two groups: Conventional (CONV) training (n = 11; age = 15.3 ± 2.1 years) and NM training (n = 11; age = 15.0 ± 2.7 years).

Interventions: Interventions were performed during a pre-season of six weeks. The CONV training included anaerobic, strength and aerobic trainings. The NM training consisted of a multi-component program that integrated jumps, landings and running with strength, endurance, agility, balance and CORE training.

Main outcome measures: A follow-up of the cohorts was carried out through the evaluation of lower limb injuries (main outcome) during a regular season (weeks 7 to 18). Secondary outcomes were measured before and after the intervention: Y-Balance Test, active joint repositioning, ground reaction force and CMJ height.

Results: The injury incidence rate was 17.89 injuries per 1000 h athlete-exposure in CONV training, and 6.58 in NM training (RR = 0.38; 95% CI = 0.18 to 0.82; $p = 0.044$). Particularly, the medial tibial stress syndrome incidence rate was 5.96 injuries per 1000 h athlete-exposure in CONV training, and 0.82 in NM training (RR = 0.17; 95% CI = 0.02 to 1.12; $p = 0.012$). In addition, a significant training x time interaction was noted favoring improvements in 30-m sprint and CMJ height after NM.

Conclusions: NM training may improve youth female athlete’s physical fitness and reduce their injury relative risk of medial tibial stress syndrome injury.

Key words: Proprioception; plyometric exercise; resistance training; athletic injuries; leg injuries; youth sports.

Introduction

Track and field (athletics) is a popular sport worldwide with international championships organized for athletes from 17 years of age. Similarly, track and field is one of the most popular high school sport for female participation, representing 15% of female participants during an interscholastic high school sport season in the United States.[1] However, individual sport athletes have a high incidence rate and prevalence of knee injuries and overload injuries.[2,3] For example, in the last 14 international championships (2007-2018) 78.2 injuries per 1000 h female athlete-exposure were observed.[4] Most of the injuries sustained by females occur during sprints (26.1%), followed by long distance running (14.1%) and jumps (11.9%).[4] However, few epidemiological studies covering cross-discipline populations of female track and field athletes have been reported.[5] This is particularly worrisome as adolescent females have a greater likelihood of major injury compared to males[6] and have the highest sport-specific injury rate in team sports.[7] Lower limb injuries are the most common, accounting for over 60% of the overall injury burden in youth sport,[1,8] particularly overuse-related conditions such as tendinopathies and stress fractures.[2] This may be related to a combination of inappropriate training loads, muscle fatigue, inadequate levels of fitness, and limited implementation of injury prevention programs.[9] Similarly, morphological-physiological development changes across the pubertal period that may predispose female athletes to greater risk of injury (e.g. knee valgus; higher navicular drop; hormone concentrations).[10,11] Indeed, adolescent female athletes have lower dynamic postural balance and a 6.5 times greater risk of suffering a lower limb injury compared to males.[12] For these reasons, reducing the risk of injury in female athletes is a difficult effort due to the interaction of intrinsic and extrinsic factors associated with regular training and competition.

Different prevention methods have been proposed to decrease the number of injuries in female athletes, such as strength training, balance training and targeted warm-up exercises.[13,14] Neuromuscular (NM) training has been proposed as a multi-component program[14,15] that integrates the development of motor skills (jumps, landings, running, etc.) with motor capacities (strength, endurance, agility, and balance) through plyometric and weight-bearing drills,[16,17] and also as a method of injury prevention.[8,15] Most prospective studies (e.g., randomized-clinical trials, quasi-experimental trials, and cohort studies) have observed a reduction in lower limb injury risk in team sports following the application of NM training, as well as an improvement in performance in the countermovement jump (CMJ), balance, and 30-m sprint, which have been widely used as tests to evaluate sports return.[14] However, among youth female track and field athletes, only one study applied CORE training focusing on strengthening the abdominal, low-back, and pelvic muscles while maintaining neuromuscular control in supine, prone and standing position.[18] Therefore, no study has evaluated the effect of NM training on the physical fitness and lower limb injury specifically in youth female track and field athletes.

In this context, the main objective of this study was (i) to determine the effects of a NM training on reducing lower limb injury incidence, and (ii) to establish its effects on CMJ performance, balance, 30-m sprint and joint position sense in youth female track and field athletes. We hypothesized that NM training offers a protective effect against injury in adolescent female athletes expressed through a reduction in the injury incidence rate and a lower injury relative risk. Additionally, it was hypothesized that NM training improves CMJ performance, balance, 30-m sprint, and joint position sense.

Methods

Design

A single-blind, randomized controlled trial was designed to determine the effects of NM training on reducing lower limb injury incidence, and to ascertain the effects of NM training on physical performance in adolescent female athletes. This trial follows the Consolidated Standards of Reporting

Trials (CONSORT) recommendations. Researchers were blinded during allocation to intervention groups. The investigation consisted of two stages; (i) physical testing (jump performance, Y-Balance test, 30-m sprint test, and joint position sense) collected before and after training interventions, which were performed during the pre-season between February and March 2019 (weeks 1 to 6); and (ii) once the intervention period had ended, a follow-up of the cohorts was carried out through the evaluation of injuries of the athletes during the regular season between March and June 2019 (weeks 7 to 18). The injury incidence rate and the injury relative risk were calculated for each training group. For this analysis, the female athletes from the NM training were considered as the exposed group and those from the CONV training as the non-exposed group. This approach was used in order to determine the possible preventive effect of NM training with a design similar to that observed in previous research.[19]

Participants

The research complied with all the relevant national regulations and institutional policies, and with the Declaration of Helsinki, and was approved by the "XXX_blind_for_review_XXX". Female track and field athletes between 11 and 18 years of age were invited to participate. Before participating in the study, all athletes and their parents were fully informed about the protocol and written informed parental consent and participant assent were obtained. The following inclusion criteria were considered: (a) youth female athletes between 11 and 18 years of age, (b) were training in athletics events such as sprinting, middle-long distance running, or hurdles with a frequency of ≥3 times per week for ≥2 hours per session, (c) to be part of an athletic organization, and (d) had participated in regional or national competitions during the last year. For this study, the following exclusion criteria were considered: (a) less than one year of continuous training, (b) sustained a lower limb injury (e.g. lateral ankle sprains; rupture of the anterior cruciate ligament; muscle tears) 6 months prior to the intervention.[16]

The sample size calculation was based on the relative risk of injury. Accepting an alpha risk of 0.05, a beta risk of 0.2 in an unilateral contrast, and an injury rate in the non-exposed group of 0.76,[3] a minimum of 11 individuals in the exposed group (NM training) and 11 individuals in the non-exposed group (conventional [CONV] training) were required to detect a minimum relative risk of 0.25.[8] As represented in the CONSORT Flow Diagram (Figure 1), from 31 initially recruited participants, 22 athletes were finally allocated through simple random sampling (automated randomization sheet) to one of two groups in a 1:1 ratio: CONV training (n = 11; age = 15.3 ± 2.1 years old; body mass = 53.7 ± 6.3 kg; height = 1.59 ± 0.05 m; body mass index [BMI] = 21.0 ± 2.3 kg.m^{-2}; maturity offset = 1.6 ± 1.2) and NM training (n = 11; age = 15.0 ± 2.7 years old; body mass = 55.4 ± 6.8 kg; height = 1.61 ± 0.02 m; BMI = 21.2 ± 2.3 kg.m^{-2}; maturity offset = 1.6 ± 1.4). The researcher who conducted the randomization did not take part in the intervention. The female athletes in each group were similar in age, height, body mass, BMI, were balanced according to athletics events i.e., sprinting-, middle- or long-distance running, and were exposed to similar training and competition schedules. The strength and conditioning coach from NM training was introduced and familiarized about theoretical and practical instructions in how to teach the exercises as well as common biomechanical mistakes. Athletes in both training interventions followed similar doses of training-competition loads. Stage of biological maturation was assessed using a previously validated regression equation applied on athletes.[20,21] Using this method, maturity offset (calculation of years from peak height velocity) was completed using the following equation:

$$
\begin{aligned}
Maturity\ Offset &= -9.376 + [0.0001882 \times Leg\ Length\ and\ Sitting\ Height\ interaction] \\
&+ [0.0022 \times Age\ and\ Leg\ Length\ interaction] \\
&+ [0.005841 \times Age\ and\ Sitting\ Heigth\ interaction] \\
&- [0.002658 \times Age\ and\ Body\ Mass\ interaction] + [0.07693 \times Body\ Mass\ by\ Height\ ratio]
\end{aligned}
$$

The body mass was assessed with a scale (Seca, Hamburg, Germany; 0.1 kg accuracy), standing and sitting height were measured using a stadiometer (Seca, model 220, USA; 0.1 cm accuracy), and the leg length (dominant) was measured from the anterior superior iliac spine to the most distal part of the medial malleolus.

Procedures

Jump Performance

Ground reaction force and vertical jump height were measured from multiple trials of a CMJ to assess jump performance. Five minutes of jogging at a comfortable speed and five submaximal CMJ were performed by each participant as a warm-up and a familiarization protocol. To measure vertical jump height and ground reaction force, participants completed three valid trials of a CMJ on a force platform (model PF-4000/50; art Oficio, Santiago, Chile) and the average was recorded.[22,23] Five minutes of rest was provided between jumps. A physical therapist (not included in the research team) supervised the performance of each jump and a valid trial required the following three criteria: (i) participants did not bend their legs in midair, (ii) participants kept their hands on their hips, (iii) and the jump was completed within the dimensions of the force platform (50 x 50 cm). A sampling frequency of 1,000 Hz was used. Data from the force platform were recorded for a period of 10 seconds while participants completed vertical jumps. Data obtained from the force platform were processed with PlataformaF software (art Oficio, Santiago, Chile), allowing the measurement of vertical jump height and ground reaction force first peak (propulsion phase) of each attempt. The ground reaction force data were digitally filtered using a bidirectional, low-pass, fourth-order Butterworth filter with a cutoff frequency of 6 Hz and were normalized to the athlete's body mass (nGRF).[22] The reliability (ICC = 0.94; CV = 2.9%) of this testing procedure has previously been demonstrated.[23]

Y-Balance Test

Postural balance was evaluated with the Y-Balance Test Kit (Functional Movement Systems, Inc., Chatham, VA, USA). Participants were allowed to practice the test twice for familiarization. The dominant lower limb was evaluated in three directions: anterior, posterolateral, and posteromedial. The dominant lower limb was determined as the limb with which athletes would kicking a ball. This procedure was repeated three times in each direction, and the average of three trials was recorded. Then, the participants rested 5 minutes and repeated the procedure with the non-dominant lower limb. A trial was classified as non-valid if the individual removed their hands from their hips, failed to return to the starting position, moved the foot of support, or loaded with the reach foot.[16,24] The reliability (ICC > 0.71; CV < 8.2%) of this testing procedure has previously been demonstrated.[20] The raw results of the Y-Balance test were normalized by dividing the distance reached by the length of the lower limb (described in previous section), and then multiplied by 100.

30-m Sprint Test

Each participant came to the testing area on the outdoor track (average wind speed 11.1 km/h; average temperature 18ºC) and were instructed to perform three trials of the 30-m sprint test at maximal effort. Sprint time was measured to the nearest 0.01 seconds using single-beam timing gates (Brower Timing System, Salt Lake City, UT, USA). Participants started in a standing position with the toe of the preferred foot positioned behind a starting line. Time was taken automatically when the athlete voluntarily initiated the test. The timing gates were positioned at the beginning (0.3 m in front of the athlete) and at 30 m; and 0.7 m above the ground (i.e., hip level). The reliability (ICC > 0.75; CV < 8%) of this testing procedure has previously been demonstrated.[25] This system enables capturing trunk movement rather than a false trigger from a limb. Each sprint was separated by 8 minutes of rest to allow for full recovery.[26] The best time from three trials was recorded.

Joint Position Sense

To evaluate the joint position sense, the active joint repositioning test of 45º and 90º knee flexion was used.[27] This method has been shown to be a valid and reliable method to assess the knee joint position sense in open kinetic chain movements.[28] The knee joint angle was measured using an electrogoniometer (PASPORT Goniometer Sensor, PS-2137, Pasco, Roseville, CA, USA) with a recording frequency of 1,024 Hz. The participants were positioned in prone and secured to allow full knee range of motion in the sagittal plane. The device was attached to the lateral aspect of the dominant lower leg using double-sided medical tape, with the proximal electrogoniometer block just above the lateral femoral condyle in line with the greater trochanter, and the distal block just below the head of the fibula, aligned with the lateral malleolus. Then, anatomical zero was measured with the knee fully extended. Each target position (45° or 90º knee flexion) was passively demonstrated with the verbal instructions "this is the testing knee position; remember what this position feels like". The target position was held there for 5 seconds by the examiner to allow the subject to memorize the position.[28] Then, the examiner slowly returned the knee to full extension. After the 5 second interval, subjects were asked to actively reproduce the target position with their eyes closed using the same leg (dominant). Participants acknowledged verbally when they deemed that they had achieved the angle. The outcome variable was the absolute angular error, which was the absolute difference between the target angle and the athlete's reproduced angle.[27] Each athlete performed a familiarization trial before the valid trial. A total of six randomized trials (three for each, 45° and 90º) were completed, and the average was taken for each target angle. To avoid any learning effect, the order of target angles was randomly allocated for each athlete.

Training Program

Conventional (CONV) Training. Athletes were asked to follow their normal track and field pre-season program between February and March 2019 (weeks 1 to 6). The CONV training was based in a previous report.[29] Athletes completed three weekly training sessions for a 6-week period. The duration of each CONV training session was 120 minutes. This included anaerobic (e.g., short sprint, technical runs, running drills), strength, and aerobic trainings (e.g., extensive/intensive tempo runs, cardiovascular circuit training). Strength training was mainly focused on free weight exercises (e.g., squat, lunge, deadlift, clean, bench press).

Neuromuscular (NM) Training. The athletes were asked to follow their normal track and field pre-season program and after 10 minutes of rest, completed NM training at the end of each session between February and March 2019 (weeks 1 to 6). The intervention period spanned six weeks and involved three weekly training sessions. The duration of each NM training session was 30 minutes. This training duration has previously been shown as a suitable exposure time for NM training.[8,19] The NM training consisted of a multi-component program that integrated jumps, landings and running with strength, endurance, agility, balance and CORE training through plyometric and body weight-bearing exercises based in previous studies.[13,15–18] Table 1 depicts the exercises completed during the NM training.

Injury Assessment

For the registration and monitoring of injuries, each athlete underwent an evaluation by a physical therapist, who consulted and reported on pain and / or lower limb injuries each week of the follow-up period (regular competition season). The injuries were registered in accordance with previous recommendations[16] and considering the following classifications: thigh muscle strain (quadriceps and hamstrings), knee bursitis, knee tendinopathy, other bone injuries (medial tibial stress syndrome or stress fracture). The incidence rate was calculated according to previous studies.[16] The *incidence rate* pertains to the number of events (injuries) in a specific period (season) divided by total athlete-exposure:

$$Incidence\ rate = \frac{Number\ of\ events\ (\#injuries)\ in\ a\ specific\ period}{Total\ athlete - exposure\ at\ risk\ in\ a\ specific\ period} \times 1000$$

Athlete-exposure corresponded to the time spent in each practice and competition by individual athletes. *Total athlete-exposure* corresponded to the time spent in each of the practices and competitions of all athletes.

Statistical Analysis

Continuous variables were presented as means ± standard deviation, while categorical variables were presented as a percentage. The normality distribution for each variable was evaluated with the Shapiro-Wilk test. To establish significant differences between training (NM and CONV) in continuous variables (nGRF, jump height, Y-Balance test performance, sprint time, and absolute angular error), a two-way analysis of variance (ANOVA) of repeated measures and t-tests corrected by Bonferroni were used. The percentage (%) change between comparisons and the effect size (ES) was calculated through Cohen's *d*, considering a trivial result (0 to 0.19), small (0.20 to 0.49), medium (0.50 to 0.79) or large (0.80 or greater). In addition, to determine differences in injury count between training programs, Fisher's exact test was used. Injury relative risk (RR) was analyzed considering all injuries accounted. The RR corresponded to the quotient between two probabilities or risks observed in the training groups. All analyses were conducted using SPSS 20.0 software for Windows, with an alpha level of $p < 0.05$ considered for all tests.

Results

All the participants were included in the study analysis since there was 100% adherence to the training plan and follow-up injuries assessments. Means ± standard deviations for all variables before and after training are presented in Table 2. The two-way ANOVA with repeated measures reported significant interactions between factors (training x time) for 30-m sprint (df = 1; $F = 4.190$; $p = 0.027$) and CMJ height (df = 1; $F = 3.454$; $p = 0.039$) in favor of NM training. Multiple comparisons showed significant differences between CONV training versus NM training after the intervention (Table 2), in favor of NM training.

CONV training presented 106.7 ± 19.8 h athlete-exposure and 1,174 h total athlete-exposure, and NM training 110.5 ± 22.6 h athlete-exposure and 1,215 h total athlete-exposure. No significant differences were observed between CONV and NM in hours of athlete-exposure ($p = 0.112$). The injury incidence rate was 17.89 (95% CI = 10.24 to 25.54) injuries per 1,000 h athlete-exposure after CONV training. In contrast, injury incidence rate was 6.58 (95% CI = 2.02 to 11.15) injuries per 1,000 h athlete-exposure after NM training. Incidence rates according to injury classification can be seen in Table 3. The injury relative risk can be seen in Figure 2 for each training.

Discussion

The main finding of this research indicates a lower injury incidence rate in track and field athletes that followed a NM training program (6.58 injuries x 1000 h athlete-exposure) compared to CONV training (17.89 injuries x 1000 h athlete-exposure) during a regular competition season; which was in addition to an overall lower relative risk for injury (RR = 0.38; $p = 0.044$). Therefore, NM training offers a protective effect against injury in female track and field athletes at the end of adolescent growth spurt (maturity offset = 1.6). The protective effect of NM training was most evident in reducing the relative risk of medial tibial stress syndrome (RR = 0.17; $p = 0.012$). Such findings complement those from published research that analyzed the effect of preventive programs (including NM training) applied throughout a regular season in team sport athletes, including sports such as basketball, soccer, volleyball, and Australian football.[8,15,17,30] Therefore, the novel findings from the current study offer valuable information regarding the protective effect a NM training program against lower limb injury when applied before the start of a regular competition season for young female individual sport athletes.

Previous reports have demonstrated that NM training warm-up programs including strength, balance, aerobic, and agility components reduce the risk of musculoskeletal injuries in team sports (IRR = 0.65; 95% IC = 0.49 to 0.86).[8,14] Indeed, several clinical trials and meta-analyses have shown that NM training possess a protective effect in reducing the incidence of anterior cruciate ligament injuries in team sport adolescent female athletes.[13,16,30] This protective effect is attributed to the fact that NM training provides somatosensory (proprioceptive) information that generates anticipatory and reactive neuromuscular responses against external and internal mechanical disturbances in the lower limb joints.[15,17,31,32] This is particularly relevant when the neuromuscular exercises are focused on the hip and knee joints.[31] However, individual sport athletes such as sprinters, middle-distance and long-distance runners not only have a high incidence rate and prevalence of knee injuries, but also a high rate an prevalence of overload injuries (non-contact) involving muscle, tendon and bone tissues of the lower leg and ankle.[2,3]

Several investigations have shown high incidence of stress fracture and medial tibial stress syndrome in track and field athletes.[5,33] Cross-country/track and field athletes have a significant relative risk value of 2.26 (95% CI = 1.18 to 4.32) for lower extremity overuse bone injury, which include stress fractures and medial tibial stress syndrome, compared to non-cross-country/track and field athletes.[34]

Similar relative risk (2.57; 95% CI = 1.18 to 5.59) for medial tibial stress syndrome was observed in our study in athletes exposed to CONV training compared to NM training. The literature has identified various risk factors for medial tibial stress syndrome, including female sex, increased body mass, higher navicular drop, previous running injury, greater hip external rotation with the hip in flexion,[35,36] and increased and longer activation of the soleus muscle during the propulsion phase of running.[37] It is possible that our NM training program helped to reduce some of the aforementioned risk factors, via improvements in the activation of ankle stabilizer muscles (thus helping to maintain foot arch),[33] increased strength of the ankle joint muscles,[38] and improved force distribution between large and small ankle joint muscles.[38] Indeed, our NM training incorporated a “ground down” and “up ground” approach, including lower limb exercises focused on unilateral weight bearing support and CORE. This might allow to improve not only the strength and neuromuscular control at the hip and knee, but also that of the ankle and foot. This would be associated with a reduction of forces in the lower leg muscle insertions, which could have a beneficial effect on injury prevention,[37] as in the current study.

Although previous NM training programs (e.g. FIFA 11+; CORE) demonstrated beneficial effects on injury risk reduction, physical fitness improvements are not always observed after such programs.[39] An improvement of both physical fitness and injury risk reduction would help to optimize training time among athletes. In this sense, a novel and relevant finding from our study indicated that our NM training approach improved both physical fitness, in addition to reduce the risk of injury. Indeed, sprint speed and CMJ height performance improved after NM training compared to CONV training. These simultaneous results may be interrelated, since an improvement in neuromuscular control, particularly in muscles such as the tibialis anterior, triceps surae and gluteus muscles, could contribute to sports performance and the prevention of injuries to the lower leg.[40] An optimization of the athlete training time may help them to devote more time to other relevant aspects of their preparation, such as technical training. In this sense, an indirect effect of the NM training program would be an increased time available for complementary training.

We acknowledge that there were some limitations to this study. *Firstly*, the study sample considered three athletics events (sprint, middle distance and long distance), which are not representative of the totality of events that athletics includes. For these reasons, the conclusions of this research should be directed only to this type of population. *Secondly*, the investigation considered a short stage of evaluation of the injury incidence rate (3-month competition). Athletes regularly have longer competitive seasons and therefore a longer period may have been a better reflection of the true risk of lower limb overuse injuries. Thirdly, in CONV training the athletes were asked to follow their normal track and field pre-season program based on the athletic event. They have specific differences in their training protocols, which could be a confusing factor in the development of the research. For these reasons, we recommend in future research to consider a more extensive injury assessment stage with special attention to lower limb overuse injuries. Finally, the NM training program considered several factors (e.g. exercises, muscle groups, motor capacities) focused on the lower limbs, without considering the possibility of which of these factors could have had a greater influence on prevention of injuries. Notwithstanding these limitations, the current study used rigorous methodologies and has provided novel and significant findings that clearly show the beneficial effects of NM training on reducing injury risk in adolescent female track and field athletes.

Conclusions

A 6-week NM training program applied before a regular season offers a protective effect against injury in adolescent female track and field athletes who are exposed to a regular training and competition season. In particular, this protective effect of NM training was most evident in reducing the incidence of medial tibial stress syndrome. Furthermore, sprint speed and CMJ height performance were improved after NM training compared to a CONV training. We recommend to practitioners the incorporation of a pre-season NM training program among youth female track and field athletes in order to improve their physical fitness and to reduce the incidence of lower limb injuries during the in-season period. As also, due to the transient nature of fitness, wherever possible practitioners should extend the NM program throughout the entire season to maximize the preventative effects of training. Finally, the NM training program should consider training elements such as CORE, power and hip-knee muscles, but should also be focused on motor capacities including balance and resistance training exercises, and distal lower limb muscles including ankle and foot.

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Figure Caption

Figure 1. CONSORT Flow Diagram.

Figure 2. Relative risk of injury after for conventional and neuromuscular training. The mean relative risk is plotted with 95% confidence interval (CI). * Injuries reaching a statistically significant value (i.e. $p < 0.05$ Fisher's exact test).

Table 1. Neuromuscular training program.

Week	Exercises	
Warm-up*	Dynamic flexibility run: lateral, posterior and anterior rocking + deep lower limb flexion + trunk rotation	4 repetitions x 10 m
	Agility run: acceleration and deceleration, anterior zigzag, posterior zigzag	4 repetitions x 30 m
1	Prone bridge (Plank)	2 repetitions x 20 s (hold)
	Supine bridge	2 repetitions x 20 s (hold)
	Side bridge	2 repetitions x 20 s (hold)
	Quadruped alternate-arm leg raises (superman)	2 sets x 20 repetitions
	Therapeutic ball wall squat	2 sets x 20 repetitions
2	Supine bridge with alternate leg extension	2 repetitions x 20 s (hold)
	Quadruped alternate-arm leg raises (superman)	2 sets x 20 repetitions
	Crossover crunch	2 repetitions x 20 s (hold)
	Step hold	2 sets x 20 repetitions x 5 s (hold)
	Multi-jump with ladder	5 sets x 1 min
	Unilateral calf raises	2 sets x 20 repetitions
	Y-Balance test in anterior, posteromedial y posterolateral directions	2 min
3	Supine bridge with alternate leg extension on therapeutic ball	2 repetitions x 20 s (hold)
	Quadruped alternate-arm leg raises (superman) on therapeutic ball	2 sets x 20 repetitions
	Front lunges	2 sets x 20 repetitions
	Lateral lunges	2 sets x 20 repetitions
	Single-legged Romanian dead lift	1 set x 10 repetitions
	Unilateral calf raises	2 sets x 20 repetitions
	Y-Balance test on BOSU in anterior, posteromedial y posterolateral directions	2 min
4	Quadruped alternate-arm leg raises (superman) on therapeutic ball	2 sets x 20 repetitions
	Side bridge	2 sets x 20 repetitions
	Jump front lunges	2 sets x 20 repetitions
	Hip-thrust (without barbell)	2 sets x 20 repetitions
	Nordic hamstring with a box	2 sets x 20 repetitions
	Single-legged lateral hop-hold	1 set x 10 repetitions
	Unilateral calf raises with dumbbells	2 sets x 20 repetitions
	Y-Balance test on BOSU in anterior, posteromedial y posterolateral directions	2 min
5	Side bridge with leg abduction	2 sets x 20 repetitions
	Jump front lunges	2 sets x 20 repetitions
	Hip-thrust (with barbell)	2 sets x 20 repetitions
	Nordic hamstring	2 sets x 20 repetitions
	Abdominal crunch with therapeutic ball	2 sets x 20 repetitions
	Single-legged lateral hop-hold	1 set x 10 repetitions
	Unilateral calf raises with dumbbells	2 sets x 20 repetitions
	Y-Balance test on BOSU in anterior, posteromedial y posterolateral directions	2 min
6	Side bridge with leg and arm abduction	2 sets x 20 repetitions
	Jump front lunges	2 sets x 20 repetitions
	Squat jump	2 sets x 20 repetitions
	Hip-thrust (without barbell)	2 sets x 20 repetitions
	Nordic hamstring on BOSU	2 sets x 20 repetitions
	Single leg tuck jump	2 sets x 20 repetitions
	Unilateral calf raises with dumbbells	2 sets x 20 repetitions
	Landing jump, hurdle and sprint	1 set x 10 repetitions

* The warm-up was applied prior to each neuromuscular training session.

Table 2. Effects of training interventions on balance, joint position sense, jump and sprint performance in youth female track and field athletes.

	Conventional Training				**Neuromuscular Training**			
	Pre	**Post**	**% Change**	**ES**	**Pre**	**Post**	**% Change**	**ES**
Y-Balance Test (%)								
Anterior – DLL	60.9 ± 7.8	69.7 ± 7.8	14.45	1.13	61.8 ± 8.5	68.8 ± 4.6	11.33	1.02
Anterolateral – DLL	94.9 ± 10.1	97.8 ± 14.8	3.06	0.23	96.8 ± 7.7	102.3 ± 11.3	5.37	0.54
Posteromedial – DLL	93.3 ± 10.3	94.5 ± 12.9	1.29	0.10	95.3 ± 9.0	97.0 ± 10.8	1.78	0.17
Anterior – No-DLL	61.8 ± 8.5	71.0 ± 9.8	14.89	1.00	62.0 ± 6.2	73.2 ± 7.7	18.06	1.60
Anterolateral – No-DLL	102.1 ± 10.3	103.0 ± 13.0	0.98	0.09	98.8 ± 11.6	102.4 ± 12.2	3.24	0.27
Posteromedial – No-DLL	97.5 ± 10.0	98.6 ± 11.5	1.13	0.10	97.6 ± 8.5	102.7 ± 12.8	4.51	0.40
Active Joint Repositioning (°AE)								
90° Knee Flexion – DLL	5.0 ± 2.7	6.2 ± 6.6	24.00	0.24	7.8 ± 6.7	5.3 ± 7.2	-32.05	0.36
45° Knee Flexion – DLL	5.2 ± 4.1	2.7 ± 2.6	-48.08	0.73	6.9 ± 5.2	3.2 ± 2.5	-53.62	0.91
90° Knee Flexion – No-DLL	5.3 ± 4.8	6.7 ± 7.1	26.42	0.23	7.4 ± 7.1	5.4 ± 8.0	-27.03	0.26
45° Knee Flexion – No-DLL	3.4 ± 1.9	2.6 ± 2.9	-23.53	0.33	7.9 ± 6.6	3.7 ± 2.9	-53.16	0.82
Jump Performance and 30-m Sprint								
30-m Sprint test (s)	5.24 ± 0.75	5.18 ± 0.23	-1.15	0.11	5.38 ± 0.36	4.82 ± 0.32*	-10.41	1.64
CMJ nGRF (Nm)	23.35 ± 2.64	23.13 ± 3.14	-0.86	0.07	22.25 ± 2.55	22.81 ± 3.25	2.70	0.21
CMJ height (cm)	15.9 ± 4.1	18.8 ± 3.4	18.24	0.77	15.9 ± 5.6	21.7 ± 2.5*	36.48	1.34

Data are expressed as mean ± standard deviation. DLL, dominant lower limb; No-DLL, no-dominant lower limb; °AE, degrees of absolute error; CMJ, countermovement jump; nGRF, normalized ground reaction force; ES, effect size. * Significant ($p < 0.05$) differences between training interventions (training x time interaction, t-tests corrected by Bonferroni).

Table 3. Injury assessments after training.

	Conventional Training			Neuromuscular Training		
Incidence Rate	**Injuries x 1000 h**	**95% confidence interval**		**Injuries x 1000 h**	**95% confidence interval**	
Injury	17.89	10.24	25.54	6.58	2.02	11.15
Thigh muscle strain	3.41	0.07	6.75	2.47	-0.32	5.26
Knee bursitis	3.41	0.07	6.75	1.65	-0.64	3.93
Knee tendinopathy	1.70	-0.66	4.06	0.82	-0.79	2.44
Medial tibial stress syndrome	5.96	1.55	10.38	0.82	-0.79	2.44
Ankle sprain	3.41	0.07	6.75	0.82	-0.79	2.44