Original Research

Trunk and hip control neuromuscular training to target inter limb asymmetry deficits associated with anterior cruciate ligament injury

Sonia Sabet [a], Amir Letafatkar [a, *], Fereshteh Eftekhari [b], Zohre Khosrokiani [a], Alli Gokeler [c]

[a] Faculty of Physical Education and Sport Sciences, Kharazmi University, Tehran, Iran
[b] Faculty of Physical Education and Sport Sciences, Shiraz University, Shiraz, Iran
[c] Luxembourg Institute of Research in Orthopedics, Sports Medicine and Science, Luxembourg

A B S T R A C T

Objective: The primary aim of this study was to determine the effect of NMT on female basketball players (performing at least 3 exercise sessions per week for at least 90 min) with inter limb asymmetry.
Design: Controlled laboratory study.
Setting: University research laboratory.
Participants: 40 female basketball players (age 22.4 ± 1.7 years, height 168.4 ± 5.31 cm, weight 66.6 ± 6.6 kg) who demonstrated neuromuscular deficits on the tuck jump test were allocated to a control group (n = 20), and the NMT group (n = 20).
Intervention: Experimental group participate in an 8-week NMT program including 6 weeks (18 sessions), each session almost lasted for 30 min.
Main outcome measures: The peak torque as well as time to peak torques of hip abductors and external rotators as well as knee flexors and extensors muscles, and the performance were measured before and at the end of a 6-week NMT using the isokinetic dynamometer and the hop test battery respectively.
Results: A significant improvement was observed in the NMT group for the peak torque and time to peak torque in hip and knee muscles both concentric and eccentric states at 60 and 180ºsec. Also, they showed a significant improvement in the distance of single leg hop and single leg triple crossover hop tests. However, no significant 20 and 21. change was seen in the control group.
Conclusions: An NMT program can significantly improve muscle strength, hop tests scores, and the inter limb asymmetry in female basketball players. The NMT may be used in ACL prevention in female basketball players with lower limb asymmetry.

© 2019 Published by Elsevier Ltd.

1. Introduction

Leg dominance has been defined as the inter-limb asymmetries resulted from an imbalance in strength, coordination and control between the two lower extremities (Myer, Ford, & Hewett, 2004; Read, Oliver, De Ste Croix, Myer, & Lloyd, 2016). Despite inconsistencies, an inter-limb asymmetries> 15% have been suggested as an indication of knee injury identified during a variety of hop tests (Barber, Noyes, Mangine, McCloskey, & Hartman, 1990; Bishop, Read, Read, & Read, 2018; Grindem et al., 2011; Impellizzeri, Rampinini, Maffiuletti, & Marcora, 2007). Previous research has

indicated that the inter-limb asymmetries tend to be greater in women than in men (Fort, Gual, Romero-Rodriguez, & Unnitha, 2016). Existing evidence has highlighted that these neuromuscular imbalances may be in line with anterior cruciate ligament (ACL) injury mechanisms (Hewett et al., 2010, 2016; Rohman, Steubs, & Tompkins, 2015). Research has estimated that knee joint injuries are accounted for almost 10%–25% of all athletic injuries (Lindsay, Maitland, Lowe, & Kane, 1992), and ACL takes up approximately 45% of these knee injuries (Avila, Brasileiro, & Salvini, 2008; Myer, Ford, & Hewett, 2008). Because basketball players must offend and defend from various directions and situations relative to the goal (Sugiyama et al., 2014), in them, the level of asymmetry is suggested to be less than the level of asymmetry in the non-basketball population (Cvorovic, 2012). Whereas, the results of Stöckel and Weigelt showed a significant difference in use between dominant and non-dominant limbs and the level of competition in which

players participate (Stockel & weigelt, 2007). An asymmetry of 10–15% can be considered as an injury reference value for male and female basketball and volleyball players (Fort et al., 2016). Thus, to reduce any asymmetry in the performance of the RSJ is essential, not only to achieve high performance, but also to prevent injury to the lower limbs (Sugiyama et al., 2014).

Lower extremity biomechanics and neuromuscular function are believed to be the most likely factors to account for the gender bias in noncontact ACL injury rates (Ford, Myer, Toms, & Hewett, 2005). According to previous research, neuromuscular training(NMT) is one of the strategies to target neuromuscular risk factors (Ford et al., 2005; Myer et al., 2008). Muscle strength, activation and synergistic coordination are essential to overall neuromuscular function and likely essential factors that could be modifiable for ACL injury prevention tactics (Hewett et al., 2016). Parameters such as time to peak torque have been established in the literature as muscle recruitment variables that provide valuable information regarding neuromuscular readiness to produce maximal contractions. The ability to produce torque quickly is an important skill in most athletic endeavors (Avila et al., 2008). The presence of these neuromuscular does not indicate an explicit causative factor for injury per se; however, it should be noted that ligamentous injuries likely occur when active muscular restraints are unable to adequately reduce joint torques during dynamic movements involving deceleration and high forces (Beynnon & Fleming, 1998; Powell & Barber-Foss, 2000). When isokinetic assessments identify muscle recruitment deficits; neuromuscular interventions could be implemented for injury prevention (Fousekis, Tsepis, & Vagenas, 2010). The effort to reduce lower extremity injuries should involve a reduction in loads or stresses on the lower extremity and improvement in technique, strength, dynamic balance, agility, that is, performance (Barber-Westin, Hermeto, & Noyes, 2010). In athletes who are not elite, the large biomechanical demands can be problematic, especially in athletes who have not developed adequate strength, aerobic fitness, and neuromuscular control to avoid common lower extremity injuries (Barber-Westin et al., 2010). The neuromuscular program could improve athletic performance indicators and biomechanics in athletes (Barber-Westin et al., 2010; Hopper, Haff, Joyce, Lloyd, & Haff, 2017; Mandelbaum et al., 2005; Myer et al., 2004, 2008; Rahimi, Alizadeh, Nouri, & Rojhani, 2014). The neuromuscular program is appropriate for pre-season training athletes or before the initiation of seasonal tournament play (Barber-Westin et al., 2010). However, the effect of NMT on biomechanical and neuromuscular movement characteristics has not been fully evaluated.

Therefore, this study aimed to determine the implication of trunk and hip control neuromuscular training in reduction strength and performance asymmetries in female basketball players measuring the concentric and eccentric isokinetic of the hip and knee muscles, and the hop test battery respectively. Finally, a hypothetical example has been included to illustrate how an athlete who displays inter-limb asymmetry in strength and performance testing could be trained to address these imbalances.

2. Materials and methods

2.1. Study design

The study took place during the collegiate sport's offseason.

2.2. Participants

Forty female basketball players with the inter-limb asymmetries between 18 and 25 years of age volunteered to participate in the study. Demographics data for the experimental and control groups

were calculated and can be found in Table 1.

The inclusion criteria were female basketball players between 18 and 25 years of age, regular sports activities in the last 3 years, a score of 13–15 in the Baecke questionnaire (Fort-Vanmeerhaeghe, Montalvo, Lloyd, Read, & Myer, 2017), and showing the inter-limb asymmetries in the plyometric tuck jump test (Hewett et al., 2016) when thighs were not parallel in the peak of the jump, feet not touched the ground simultaneously, and feet not placed parallel to each other (Myer et al., 2008). Exclusion criteria included: history of hip, ankle, and knee joint injuries, chronic tendinopathy, muscle strain, and or ligament sprain (all grades) injuries in the past 6 months, history of lower limb surgery, free from chronic musculoskeletal conditions; and free from visual, vestibular (eg, vertigo), or sensory conditions (eg, diabetes) that could negatively affect their postural control, injury during the course of the study that prevented exercise, absenteeism for more than 2 regular sessions, and 3 irregular sessions in performing instruction exercises, participation in the instruction exercises during the last year, and the feeling of pain at the time of the research (Zahradnik, Jandacka, Uchytil, Farana, & Hamill, 2015).

An experienced physiotherapist assessed the subjects based on clinical history, posture and symptom responses to active movements. For all the assessments, the assessor was blinded to the group allocation. The data analyst was also blinded to the treatment allocation.

Before conducting the research, the subjects signed the written consent form. The study was approved by the Institutional Review Board (IRB) in the spirit of the Helsinki Declaration. Risk and benefits of study participation were individually explained to the subjects.

Randomization was included a fixed-size design with a concealed allocation ratio of 1:1. Based on their recruitment, each participant picked up a concealed envelope assigned to a type of treatment. Thus, the participants were assigned to the exprimental(n = 20) or control groups(n = 20).

2.3. Procedures

This study involved the collection of demographic information, level of physical activity, the dominant leg, and performance on the tuck jump test to determine leg dominance (LD), for each subject (Fousekis et al., 2010). The tuck jump test has been found to be a reliable assessment for asymmetry within athletes (Myer, Brent, & Hewett, 2011). The dominant leg was defined as the preferred limb used to kick a ball for maximum distance (Barber-Westin et al., 2010).

The experimental group performed the NMT program, based on the study of Myer et al. (2008) (Myer et al., 2008), approximately 30 min a session with 10 min of warm-up and cool-down, 3 sessions a week for 6 weeks with each session separated by at least 1 day.

The techniques were presented individually to each subject, and one expert supervised all training sessions. All subjects were instructed to maintain their regular off-season regime. However,

Table 1
Group demographics[*].

Characteristic	NT (N = 20)	Control (N = 20)	sig
Age M(SD) (years)	23.42(1.72)	22.45(1.68)	0.91
Height M(SD) (cm)	169.31(4.25)	167.52(6.37)	0.86
Mass M(SD) (kg)	65.43(5.43)	67.71(6.57)	0.61
Exercise experience M(SD) (years)	8.43(2.34)	9.62(1.56)	0.08

[*]Values are mean ± SD.
Abbreviations: NT: neuromuscular training.

control subjects received no intervention and continued their regular off-season regime accounted for 3 sessions a week for 6 weeks with each session separated by at least 1 day.

The order of tests was randomized for each participant, but were performed in the same order at the pre- and posttesting sessions. The Isokinetic test and Hop tests were performed in the separate days to minimize the effect of fatigue. The intervention subjects began NMT within 1 week after the baseline data collection session. All subjects returned for a second data collection session within one week after performing NMT. The baseline and the second data procdures were the same. For the baseline and post intervention data, the assessor was blinded to the group allocation.

2.4. The inter-limb asymmetry assessment with the tuck jump test

The tuck jump assessment allows a coach or clinician to evaluate an athlete's risk of injury as well as identify specific deficiencies (Myer et al., 2011).

The inter-limb asymmetry was defined in the tuck jump test when thighs were not parallel in the peak of the jump, feet not touched the ground simultaneously, and feet not placed parallel to each other (Myer et al., 2008).

The tuck jump test was assessed based on the study of Myer et al. (2008) by an experienced tester (Myer et al., 2008). Digital cameras were used to enterpret the movement and to identify athlete with the inter-limb asymmetries. The cameras were placed as close as possible to the subject to interpret more reliable data (Myer et al., 2008).

The subjects were trained to land at the starting position and continue to jump for 10 s (Myer et al., 2008). The accurate technique of the jump test was explained to the subjects.

2.5. Measuring the performance, using the single leg hop and single leg triple crossover hop tests for distance

The secondary outcome was performance, using two reliable single leg hop(ICC > 0.85) and single leg triple crossover hop tests for distance(ICC > 0.85) (Barber-Westin et al., 2010). Each hop tests were performed twice on each leg(dominant and non-dominant), and every distance was recorded based on the study of Noyes et la.,(1991) (Noyes, Barber, & Mangine, 1991). Subjects could practice 2 trails before commencing the measurement of the hop tests. Subjects performed 3 trials with at least 2 min of rest between them, to assure that subjects could reach the maximum possible distance.

Errors in execution involved: touching the other leg, touching the ground by hand(s), losing balance, and performing excessive hopping during landing. Subjects should repeat the execution if they did any errors (Barber-Westin et al., 2010).

2.6. Measuring the strength of hip and knee muscles using an isokinetic dynamometer

The concentric and eccentric strength of hip abductors and external rotators as well as knee flexors and extensors muscles was measured with an isokinetic dynamometer (Biodex Medical Systems, Shirly, NY).

The subjects were informed about the procedures of hip abduction and hip external rotation torque tests. The hip abduction and external rotation torque tests were conducted in dominant and non-dominant legs in a random order. The test began with the hip abduction torque test, with the subject in side-lying position (Baldon et al., 2009; Lindsay et al., 1992) with the non-tested hip and knee flexed and fixed with straps. The dynamometer's rotation axis was aligned with a point on the participant representing the

intersection of 2 straight lines. One line was directed inferiorly from the posterior-superior iliac spine toward the knee, and the other line was medially directed from the greater trochanter of the femur toward the midline of the body. The lever arm of the dynamometer was attached with straps five cm above the superior border of the patella. The hip was placed in a position that was neutrally aligned in all three planes. The subjects were instructed to keep their toes pointed forward and not to bend their knees to help prevent alterations in muscle recruitment and compensation during testing.

The range of motion of the test was from 0° (neutral position) to 30° of hip abduction (Baldon et al., 2009; Lindsay et al., 1992). Before conducting the test, each subject performed a 5-min sub maximal warm-up on an ergometer. The dynamometer was calibrated each day of testing.

The subjects performed two series of five sub-maximal and 1 serie of 5 maximal reciprocal hip abduction familiarisation contractions with a one-minute rest interval between the 2 series. After a three-minute rest interval, subjects performed 2 sets of 5 repetitions at their maximal voluntary effort with three-minute rest intervals between sets. Next, the hip external familiarisation procedures and torque tests were performed. External hip rotation isokinetic peak torque was measured with the subject seated and the hip and knee flexed to 90° (Baldon et al., 2009; Lindsay et al., 1992). The axis of the dynamometer was aligned with the long axis of the femur. The range of motion of the test was from 0° (neutral position) to 30° of external hip rotation.

Verbal encouragement was provided to assure maximal effort for the hip torque tests. The movements were performed at an angular speed of 60°/s and 180°/s (Baldon et al., 2009; Lindsay et al., 1992). To correct the influence of gravity effect torque on the data, the limb was weighed following the instructions from the dynamometer's operations manual. Test results were automatically corrected in the software for gravity effect torque.

Repetitions were excluded if the participant was not able to execute the movement through the total range of movement during the eccentric torque test or if the torque value was inferior to 80% of the peak torque values of the last 5 repetitions. To obtain reliable results, we excluded 2 repetitions from the hip abduction torque test and three repetitions from the hip external rotation torque test for all subjects, based on the performance of most subjects. We used the peak torque value of the last 5 maximal contractions to calculate the mean peak torque value, but if we excluded a repetition, the mean peak torque value was calculated using the peak torque value from the last 4 repetitions of the test (Baldon et al., 2009).

Then, the concentric and eccentric torque of the knee flexor and extensor were measured in both dominant and non-dominant legs. The measurement was done at angular velocities of 60°, 180°/sec for concentric strength and an angular velocity of 60°/sec for eccentric strength at the peak extension and flexion of the knee joint (Fousekis et al., 2010). Initially, the subjects were asked to have a seated position (90° hip and knee angle). The upper trunk was fixed and stabilized by the stripper in the shoulder, chest, and thigh. The knee axis was also aligned with the dynamometer shaft. The isokinetic test range was set between 0° and 90° flexion. The subject was taught to take the handle near the seat during the test and then perform the three submaximal, and maximal affords (for familiarisation) of flexion and extension. Then, 5 consecutive maximal repetitions were performed by each subject (Fousekis et al., 2010), and after each angular velocity in one leg, a 3-min rest and then another leg began. The dominant leg measurement was conducted before the non-dominant one (Lindsay et al., 1992). Dominant leg was defined as the leg used to kick a ball for maximum distance (Barber-Westin et al., 2010). The factors analyzed in this study were: 1) Peak torque for a set consisting of 5

isokinetic repetitions for each side of the body; 2) Time to reach peak torque for each side of the lower extremities (dominant vs non-dominant). (Lee & Han, 2016).

2.7. Limb symmetry index

Typically, functional tests are scored using a measure known as the Limb Symmetry Index (LSI). The LSI is measured by dividing the nondominant limb's score by the dominant limb's score, yielding a percentage (non-dominant leg/dominant leg × 100). In this system, 100% indicates perfectly symmetric performance (Rohman & Tompkins, 2014).

2.8. Neuromuscular training

In this study, the training protocol was based on the study of Myer et al. (2008) (Myer et al., 2008) and performed for 6 weeks (18 sessions). The training was conducted using weights, medicine balls, steppes, bosu ball (NAUM, South Korea) and Swiss balls. Each session took about 30 min with ten-minute warm-up and cool-down. The subjects were informed about the proper techniques in the first session by an instructor expertise in all exercises.

The training was designed in 5 phases; each phase was increased progressively so that at the beginning, the training was done in a simple form, with less volume, and with both legs and excellent technique and relative ease. Gradually, it progressed and became more difficult, based on the subjects' ability and function. Once the instructor becomes certain about the proficiency of an individual athlete's techniques in all exercises, the athlete can advance to the next phase. The athlete should perform the exercises at the prescribed volume and intensity with proper technique. The athlete should be trained in the proper technique of each exercise with feedback whenever needed.

Subjects with 3 non-consecutive sessions and 2 consecutive sessions of absences in training sessions were excluded from the study.

2.9. Statistical analysis

A priori power analysis (G*Power, version 3.1.2) was performed to determine the appropriate sample size for the entirety of the study, which dichotomized control and intervention groups by sport. For this two-group design, 20 participants per group were determined to be adequate to achieve 80% power at a statistical

significance criterion of 0.05 with a moderate effect size (0.38). This effect size was comparable to other studies that reported changes in hip and knee biomechanics after training (Lephart et al., 2005; Taylor et al., 2018a).

Shapiro-Wilk and Levene tests were used to assess the distribution and homogeneity of variance before performing analysis of covariance respectively (ANOVA).

Descriptive data were calculated for all variables. A mixed-design repeated measure ANOVA (2×2) was used to test for interactions and main effects for time (pre-vs. posttest) and group (NMT exercises vs. control) on the strength and performance variables. Statistical analyses were conducted in SPSS (SPSS, Version 18.0, Chicago; IL). Statistical significance was established a priori at $p < 0.05$ to test the directional(one-sided) hypothesis that NMT exercises would be more effective than control in improving strength and performance in active female participants.

The effect size (Cohen's d) was calculated to determine the magnitude of the difference between groups and was interpreted as small if $d \leq 0.5$, moderate $d = 0.5-0.8$ and large d˃0.8 (Portney & Watkins, 2009).

3. Results

The NMT and control groups had a participation rate of 100% during the study. A significant interaction of group and time was observed following the study with selected strength and performance measures which indicate that training responses were different between NMT and the control.

The results of the Shapiro-Wilk test indicated normal data distribution. Table 1 represents the mean and standard deviation of the demographic characteristics of subjects.

Based on the results of repeated measurements analysis of variance with Greenhouse–Geisser test significant group × time interactions were noted in all variables (Table 2- 4). Pretest comparisons revealed no significant differences between groups at baseline testing for all variables.

3.1. Single leg hop, and single leg triple crossover hop performance

Posttest comparisons revealed significant differences between and within groups in single leg hop and single leg triple crossover hop tests for both dominant and non-dominant limbs as well as LSI ($p < 0.05$). However, there was no significant difference between the pre-test and post-test in the control group (Table 2).

Table 2
Intra- and inter-group differences for performance (Single leg hop and single leg triple crossover hop for distance) tests.

Performance	Leg	NT (N = 20)		Control (N = 20)		Interaction effect F(P $_{value}$)	Intra-group differences	Inter-group differences
		Pre, M(SD)	Post, M(SD)	Pre, M(SD)	Post, M(SD)			
Single leg hop (m)	D	1.35(0.15)	1.66(0.17)	1.39(0.13)	1.33(0.07)	14.23(0.001)€	Experimental = 0.001* Control = 0.094	P = 0.028¥ Effect size(95% CI): 0.72(0.15−2.29)
	ND	1.13(0.11)	1.57(0.10)	1.15(0.13)	1.08(0.12)	12.15(0.024) €	Experimental = 0.004* Control = 0.204	P = 0.018¥ Effect size(95% CI): 0.83(0.25−2.42)
	LSI (%)	84.8(5.2)	95.5(3.7)	82.7(4.1)	81.2(6.4)	10.53(0.031) €	Experimental = 0.008* Control = 0.099	P = 0.034¥ Effect size(95% CI): 0.67(0.11−2.23)
Single leg triple crossover hop (m)	D	3.53(0.19)	3.88(0.19)	3.43(0.25)	3.29(0.13)	15.16(0.002) €	Experimental = 0.001* Control = 0.119	P = 0.031¥ Effect size(95% CI): 0.69(0.13−2.26)
	ND	3.05(0.17)	3.70(0.18)	3.02(0.18)	2.91(0.04)	13.27(0.007) €	Experimental = 0.003* Control = 0.118	P = 0.021¥ Effect size(95% CI): 0.79(0.22−2.37)
	LSI (%)	86.4(4.3)	95.3(2.6)	88(1.8)	88.4(2.4)	10.12(0.037) €	Experimental = 0.009* Control = 0.105	P = 0.023¥ Effect size(95% CI): 0.77 (0.2−2.35)

Abbreviations: NT: neuromuscular training; D, dominant; ND, non-dominant; LSI, limb symmetry index (non-dominant leg/dominant leg × 100); ES, Effect size; 95% CI, 95% confidence interval.
Values are mean (SD); * Intra-group difference; ¥ Inter-group differences.
€ significant time × group interaction.

3.2. Knee flexion peak torque and time to peak torque

Posttest comparisons revealed significant differences between and within groups in Peak torque and Time to Peak torque, flexion at 180°/S and 60°/S for both dominant and non-dominant limbs as well as LSI(p < 0.05). However, there was no significant difference between the pre-test and post-test in the control group (Table 3).

3.3. Knee extension peak torque and time to peak torque

Posttest comparisons revealed significant differences between and within groups in Peak torque and Time to Peak torque extension at 180°/S and 60°/S for both dominant and non-dominant limbs as well as LSI(p < 0.05). However, there was no significant difference between the pre-test and post-test in the control group (Table 3).

3.4. Hip abduction and external rotation peak torque and time to peak torque

Posttest comparisons revealed significant differences between and within groups in Peak torque and Time to Peak torque hip abduction, and external rotation at 180°/S and 60°/S for both dominant and non-dominant limbs as well as LSI(p < 0.05). However, there was no significant difference between the pre-test and post-test in the control group(Table 4).

4. Discussion

The purpose of this study was to determine the effect of trunk and hip control NMT in reduction between-limb strength and performance asymmetries in female basketball players. Results of the current study demonstrated significant improvements in the knee and hip-joint isokinetic related variables and performance in both single leg hop, and single-leg triple crossover hop tests in comparison to the control group.

Single leg hop and single leg triple crossover hop tests for distance showed initial LSI of 84.8% and 86.4% in performance and improved significantly to 95.5% and 95.3% respectively for the NMT group after NMT. Although the minimal clinically relevant change for LSI has not been ascertained, this outcome could uphold a high utility for NMT in functional improvement.

The neuromuscular deficits between limbs could be attributed primarily to the specific neuromuscular requirements of each particular sport. Clinicians often make a decision about sufficiently recovered athletes from an injury, based on accepted benchmark of the strength and dynamic functional outcome measures. Based on the commonly accepted benchmark, at least >94% may need to be considered as reflective of adequate performance compared to the healthy uninjured populations (McGratha et al., 2016).

Dynamic neuromuscular training applied to the female athletes with neuromuscular deficits may decrease knee-injury incidence and help biomechanical performance in athletic activities (Myer et al., 2004). Our results agree with Barber-Westin at al. (2009) and Rohman et al. (2015) who showed early improvements in both limbs, followed by continued improvements in the LSI for performance during NMT (Barber-Westin et al., 2010; Rohman et al., 2015).

Regarding the initial limb dominance on strength measures, our study revealed statistically significant improvement on LSI between dominant and non-dominant leg peak torque, and time to peak torque between knee flexors and extensors at 60°/S and 180°/S knee angles during the treatment in females with inter limb asymmetries. To be sure about the result of the training based on LSI, it is beneficial to measure the undominant limb performance (Rohman et al., 2015). Results showed that an increased LSI in our study reflects a true increase in the limbs' function, rather than a decrease in the ability of one limb because of NMT on the strength (Rohman et al., 2015).

Specifically, functional asymmetries have been shown for the lower legs of female athletes of different skills (Bishop et al., 2018; Ford et al., 2005; Fort et al., 2016; Hewett et al., 2010, 2016; Impellizzeri et al., 2007; Mandelbaum et al., 2005; Myer et al., 2008; Rohman et al., 2015; Taylor et al., 2018b). Previous research reported NMT training programs could improve the peak torque of knee flexors and extensors ratio in both legs by improving neuromuscular control and asymmetry in female athletes (Dello Iacono, Padulo, & Ayalon, 2016; Letafatkar, Rajabi, Tekamejani, & Minoonejad, 2015; Singh, Boyat, & Sandhu, 2015). Lee and Han. (2016) also observed a significant improvement in the isokinetic strength of the knee and lumbus muscles using complex core balance training (Lee & Han, 2016). Furthermore, based on the research of Rahimi et al. (2014), improving knee joint muscles' strength at the dominant and non-dominant leg could potentially result in reducing knee torque changes and the risk of ACL injury rates (Rahimi et al., 2014).

There would be a statistically positive significant correlation between hop tests and isokinetic knee strength (Sueyoshi, Nakahata, Emoto, & Yuasa, 2010). However, reviewed studies by Fitzgerald et al. suggested that the correlation between the hop tests and knee strength varied among studies. The different hop tests could be accounted for disagreement in study results. The hop tests used in the previous studies varied, and this could be regarded as one of the factors why past studies failed to establish a correlation between the results of hop tests and knee strength. Our results agree with the findings of Suyoshi et al. (2012) indicating that the findings of the hop tests and isokinetic knee strength are related in measuring initial LSI asymmetry and improvement during NMT (Sueyoshi et al., 2010).

Our study suggests that lower limb muscular strength develops symmetrically in single-leg-dominant athletes during NMT. A possible explanation for these results is that while one leg exerts its specific exercise, the other leg remains active, providing postural stabilizing, to support the individual's weight (Vaisman et al., 2017), considering each leg should perform any exercise as exerting or supporting the action. Note that maximum cross-over effects are achieved when both lower extremities are utilized in single limb activities, alternately. Additionally, single leg activities used in this study may influence the synergistic recruitment of the posterior chain musculature, which not only facilitates the muscular control with unilateral tasks but may also decrease quadriceps dominance during dynamic tasks (Hewett et al., 2010).

Regarding the initial limb dominance on strength measures, our study also revealed statistically significant improvement on LSI between dominant and non-dominant leg for hip Abduction, and external rotation peak torque and time to peak torque at 60°/S and 180°/S during the treatment for females with LD. Again, an increased LSI in our study reflects a true increase in the function of the limbs, rather than a decrease in the ability of one limb because of NT on the strength (Rohman et al., 2015).

Using a combination of unilateral and bilateral strengthening and jumping-based exercises, Sannicandro, Cofano, Rosa, and Piccinno (2014) reported an effective method for reducing between-limb differences (Sannicandro et al., 2014). Based on the results of the study of Gonzalo-Skok et al. (2017), it could initially be suggested that unilateral training is superior to bilateral training at reducing inter-limb asymmetries and may also have a more positive effect on speed and performance as well (Gonzalo-Skok et al., 2017). Finally, Brown et al. (2017) conducted a case study (N = 1) and showed a 26% increase in horizontal force (effect size = 2.2) for

Table 3
Intra- and inter-group differences for Knee Flexion and extension Peak Torque and time to peak torque variables.

	Variable	Leg	NT (N = 20) Pre, M(SD)	Post, M(SD)	Control (N = 20) Pre, M(SD)	Post, M(SD)	Interaction effect F(P value)	Intra-group differences	Inter-group differences
Flexion	Peak torque, 180°/S	D	57.8(4.9)	67.5(5.3)	59.3(6.7)	57.3(5.4)	27.15(0.029) €	Experimental = 0.031* Control = 0.099	P = 0.040¥ ES(95% CI): 0.63 (0.07 −2.18)
		ND	45.3(5)	66.1(5.1)	46.2(6.4)	46.4(4.9)	29.21(0.025) €	Experimental = 0.021* Control = 0.108	P = 0.037¥ ES(95% CI): 0.65 (0.09 −2.21)
		LSI (%)	78.3(6.2)	97.9(5.6)	77.9(5.6)	80.9(4.3)	31.53(0.019) €	Experimental = 0.008* Control = 0.093	P = 0.044¥ ES(95% CI): 0.60 (0.05 −2.15)
	Time to Peak torque,180°/S	D	291.5(24.8)	244.4(22.7)	287.6(24.2)	279(21.8)	65.64(0.001) €	Experimental = 0.003* Control = 0.089	P = 0.035¥ ES(95% CI): 0.72 (0.10 −2.22)
		ND	336.9(75.4)	263.3(41.2)	393.8(49.5)	382.1(58.6)	52.11(0.001) €	Experimental = 0.001* Control = 0.095	P = 0.034¥ ES(95% CI): 0.67 (0.11 −2.23)
		LSI (%)	115.5(6.7)	107.7(7.9)	136.9(12.4)	136.9(8.2)	36.02(0.001) €	Experimental = 0.004* Control = 0.085	P = 0.018¥ ES(95% CI): 0.83 (0.25 −2.42)
	Peak torque, 60°/S	D	92.4(12.8)	153.7(13.7)	95.1(7.1)	81.7(6.2)	42.24(0.001) €	Experimental = 0.002* Control = 0.079	P = 0.033¥ ES(95% CI): 0.68 (0.12 −2.24)
		ND	69(5.6)	139.8(8.3)	63.2(5.1)	61.5(6.4)	35.33(0.001) €	Experimental = 0.001* Control = 0.201	P = 0.004¥ ES(95% CI): 1.21 (0.57 −2.86)
		LSI (%)	74.6(5.1)	90.9(12.4)	66.4(4.3)	70.9(4.5)	24.11(0.003) €	Experimental = 0.001* Control = 0.194	P = 0.024¥ ES(95% CI): 0.76 (0.19 −2.33)
	Time to Peak torque, 60°/S	D	411.3(48.3)	374.3(23.5)	417.6(39.2)	421.5(36.4)	62.43(0.003) €	Experimental = 0.001* Control = 0.207	P = 0.029¥ ES(95% CI): 0.71 (0.14 −2.28)
		ND	433(43.7)	379.6(32.7)	439.2(31.2)	450.7(27.3)	65.53(0.003) €	Experimental = 0.003* Control = 0.102	P = 0.037¥ ES(95% CI): 0.65 (0.09 −2.21)
		LSI (%)	105.2(3.3)	101.4(2.5)	105.1(2.7)	106.9(2.9)	34.49(0.028) €	Experimental = 0.021* Control = 0.459	P = 0.007¥ ES(95% CI): 1.07 (0.45 −2.70)
Extension	Peak torque, 180°/S	D	94.1(7.9)	113.8(7.1)	97.2(7.2)	96.2(8.3)	21.47(0.014) €	Experimental = 0.007* Control = 0.475	P = 0.041¥ ES(95% CI): 0.62 (0.07 −2.18)
		ND	81.6(6.8)	111.9(7.7)	80.4(6.3)	80.7(6.4)	29.43(0.008) €	Experimental = 0.001* Control = 0.533	P = 0.003¥ ES(95% CI): 1.29 (0.63 −2.95)
		LSI (%)	76.7(3.7)	98.3(3.9)	82.7(2.8)	83.8(3.9)	24.89(0.009) €	Experimental = 0.001* Control = 0.427	P = 0.006¥ ES(95% CI): 1.11 (0.48 −2.74)
	Time to Peak torque, 180°/S	D	316.9(24.4)	258.3(21.5)	311.5(26.5)	316.3(27.6)	65.21(0.001) €	Experimental = 0.002* Control = 0.125	P = 0.039¥ ES(95% CI): 0.63 (0.08 −2.19)
		ND	330(20.7)	251.8(21.6)	361.5(17.3)	372.3(26.1)	71.37(0.001) €	Experimental = 0.002* Control = 0.079	P = 0.036¥ ES(95% CI): 0.65 (0.10 −2.21)
		LSI (%)	104.1(3.2)	97.4(3)	116(3.8)	120.8(3.5)	25.28(0.019) €	Experimental = 0.027* Control = 0.201	P = 0.019¥ ES(95% CI): 0.82 (0.24 −2.40)
	Peak torque, 60°/S	D	143.9(7.7)	168.2(7.9)	146.4(13.4)	149.5(11)	52.27(0.001) €	Experimental = 0.003* Control = 0.321	P = 0.028¥ ES(95% CI): 0.72 (0.15 −2.29)
		ND	120.6(9.5)	165.4(11)	117.1(14.7)	131.7(8.5)	46.12(0.001) €	Experimental = 0.002* Control = 0.109	P = 0.024¥ ES(95% CI): 0.76 (0.19 −2.33)
		LSI (%)	83.8(2.3)	98.3(1.4)	79.9(2.2)	88(2.3)	29.37(0.023) €	Experimental = 0.021* Control = 0.098	P = 0.031¥ ES(95% CI): 0.69 (0.13 −2.26)
	Time to Peak torque, 60°/S	D	388.4(23.3)	319.9(24.6)	370.7(21.2)	380.9(19.6)	68.67(0.001) €	Experimental = 0.002* Control = 0.121	P = 0.025¥ ES(95% CI): 0.75 (0.18 −2.32)
		ND	418.4(17.7)	326(21)	406.3(23.6)	417.9(22.4)	79.21(0.001) €	Experimental = 0.001* Control = 0.123	P = 0.014¥ ES(95% CI): 0.90 (0.30 −2.49)
		LSI (%)	107.7(1.5)	101.9(2.1)	109.6(2.2)	109.7(1.7)	17.15(0.031) €	Experimental = 0.016* Control = 0.323	P = 0.006¥ ES(95% CI): 1.11 (0.48 −2.74)

Abbreviations: NT: neuromuscular training; D, dominant; ND, non-dominant; LSI, limb symmetry index (non-dominant leg/dominant leg × 100); ES, Effect size; 95% CI, 95% confidence interval.
Values are mean (SD); * Intra-group difference; ¥ Inter-group differences.
€ significant time × group interaction.

Table 4
Intra- and inter-group differences for hip Abduction, and External Rotation Peak Torque and time to peak torque variables.

Abduction		Leg	NT (N = 20)		Control (N = 20)		Interaction effect F(P value)	Intra-group differences	Inter-group differences
			Pre, M(SD)	Post, M(SD)	Pre, M(SD)	Post, M(SD)			
	Peak torque, 180°/S	D	88.5(5.9)	120.3(8.1)	86.7(7.3)	83.1(7.1)	36.72(0.001) €	Experimental = 0.007* Control = 0.234	P = 0.016¥ ES(95% CI): 0.86 (0.28 −2.45)
		ND	76 (9.6)	111(9.7)	67.4(8.6)	71.4(8.6)	39.11(0.001) €	Experimental = 0.001* Control = 0.173	P = 0.011¥ ES(95% CI): 0.96 (0.36 −2.56)
		LSI(%)	85.8(3.1)	92.2(1.2)	77.7(2.6)	85.9(2.5)	19.52(0.032) €	Experimental = 0.001* Control = 0.129	P = 0.007¥ ES(95% CI): 1.07 (0.45 −2.70)
	Time to Peak torque, 180°/S	D	322 (26.1)	230.1(19.2)	345.4(26.5)	355.3(26.3)	57.16(0.001) €	Experimental = 0.002* Control = 0.241	P = 0.004¥ ES(95% CI): 1.21 (0.57 −2.86)
		ND	347.4(28.3)	240.5(19.2)	372.4(26.7)	379(22.1)	72.23(0.001) €	Experimental = 0.001* Control = 0.428	P = 0.002¥ ES(95% CI): 1.39 (0.71 −3.07)
		LSI(%)	107.8(3.3)	104.5(2.8)	107.8(3.1)	106.6(1.2)	10.32(0.043) €	Experimental = 0.001* Control = 0.334	P = 0.011¥ ES(95% CI): 0.96 (0.36 −2.56)
	Peak torque, 60°/S	D	97.2(9.5)	156.6(7.1)	91.7(6.4)	89.8(9.5	31.35(0.003) €	Experimental = 0.003* Control = 0.179	P = 0.006¥ ES(95% CI): 1.11 (0.48 −2.74)
		ND	85.1(9.4)	145.6(7.1)	80.5(8.5)	73.8(8.4	32.02(0.003) €	Experimental = 0.001* Control = 0.168	P = 0.013¥ ES(95% CI): 0.92 (0.32 −2.51)
		LSI(%)	87.5(2.2)	92.9(1.6)	87.7(2.4)	82.1(1.3)	11.12(0.037) €	Experimental = 0.005* Control = 0.213	P = 0.012¥ ES(95% CI): 0.94 (0.34 −2.54)
	Time to Peak torqu, 60°/S	D	220.3(14.1)	170.4(14.3)	210.4(23.8)	217.8(14)	67.23(0.001) €	Experimental = 0.001* Control = 0.222	P = 0.007¥ ES(95% CI): 1.07 (0.45 −2.70)
		ND	251.4(18.1)	181.3(12.3)	246.3(22.5)	256.4(13.6)	67.26(0.001) €	Experimental = 0.001* Control = 0.412	P = 0.014¥ ES(95% CI): 0.90 (0.30 −2.49)
		LSI(%)	114.1(1.9)	106.3(1.6)	117(1.4)	117.7(2.5)	13.32(0.037) €	Experimental = 0.007* Control = 0.549	P = 0.001¥ ES(95% CI): 1.57 (0.85 −3.28)
external rotation	Peak torque, 180°/S	D	51.3(8.1)	79.4(8.6)	50.5(7.4)	52.5(5.5)	24.27(0.009) €	Experimental = 0.001* Control = 0.423	P = 0.029¥ ES(95% CI): 0.71 (0.14 −2.28)
		ND	41.1(5.1)	74.4(6.17)	43.7(8.6)	42.3(7.1)	26.67(0.009) €	Experimental = 0.001* Control = 0.368	P = 0.032¥ ES(95% CI): 0.69 (0.12 −2.25)
		LSI (%)	80.1(3.2)	93.7(2.8)	86.4(3.4)	80.5(3.4)	16.38(0.031) €	Experimental = 0.008* Control = 0.121	P = 0.041¥ ES(95% CI): 0.62 (0.7 −2.18)
	Time to Peak torque, 180°/S	D	302.3(25)	228.4(25.5)	307.4(27)	301.4(22.1)	24.18(0.008) €	Experimental = 0.001* Control = 0.109	P = 0.008¥ ES(95% CI): 1.04 (0.42 −2.66)
		ND	326.1(28.2)	236.4(32.2)	312.4(29.4)	321.4(27.2)	17.43(0.018) €	Experimental = 0.002* Control = 0.123	P = 0.003¥ ES(95% CI): 1.29 (0.63 −2.95)
		LSI(%)	107.8(2.2)	103.5(2.9)	101.6(1.2)	106.6(1.4)	10.23(0.041) €	Experimental = 0.003* Control = 0.106	P = 0.017¥ ES(95% CI): 0.85 (0.26 −2.44)
	Peak torque, 60°/S	D	81.3(7.1)	129.4(9.3)	87.1(7.4)	86.5(8.4)	26.56(0.003) €	Experimental = 0.001* Control = 0.638	P = 0.033¥ ES(95% CI): 0.68 (0.12 −2.24)
		ND	57.7(8.5)	121.3(8.4)	54.2(5.2)	52.5(6.3)	32.34(0.001) €	Experimental = 0.001* Control = 0.458	P = 0.024¥ ES(95% CI): 0.76 (0.19 −2.33)
		LSI (%)	70.9(3.3)	93.7(2.2)	62.2(3.8)	60.6(2.6)	24.57(0.001) €	Experimental = 0.001* Control = 0.599	P = 0.005¥ ES(95% CI): 1.16 (0.52 −2.79)
	Time to Peak torque, 60°/S	D	335.3(28.3)	285.2(21.3)	328.3(24.4)	325.3(32.8)	46.52(0.001) €	Experimental = 0.005* Control = 0.589	P = 0.034¥ ES(95% CI): 0.67 (0.11 −2.23)
		ND	367.1(28.1)	290.6(32.7)	355.2(25.3)	363.5(25.7)	63.12(0.001) €	Experimental = 0.001* Control = 0.324	P = 0.016¥ ES(95% CI): 0.72 (0.28 −2.45)
		LSI(%)	109.4(1.9)	101.8(2.5)	108.1(2.5)	111.74(2)	13.22(0.034) €	Experimental = 0.007* Control = 0.174	P = 0.003¥ ES(95% CI): 1.29 (0.63 −2.95)

Abbreviations: NT: neuromuscular training; D, dominant; ND, non-dominant; LSI, limb symmetry index (non-dominant leg/dominant leg × 100); ES, Effect size; 95% CI, 95% confidence interval.
Values are mean (SD); * Intra-group difference; ¥ Inter-group differences.
€ significant time × group interaction.

the weaker limb; however, changes for the stronger limb were 'unclear'. (Brown et al., 2017).

As in all studies, limitations arise that can affect the results. First, it is not possible to generalize the results to female athletes participating in another type of sports or different level of sports, and to male athletes with different ages. Also, we did not measure the dynamic knee valgus which is one of the common causes of ACL injury. Because this is a retrospective case-control study design identify asymmetry differences between DL and NDL in female basketball players after asymmetry has occurred, it is possible that the differences were not present before the asymmetry and occurred as a response to the asymmetry. Some investigations need to be performed to identify the effect of the NMT on the factors that predict asymmetry with prospectively identifying asymmetry incidence. We examined only the short-term effects of NMT. Future research is required to understand the neuromuscular factors as well as to determine the long-term effect of an integrated NMT program on the active females with inter limb asymmetries. Finally, it seems using another reliable instrument like EMG could make the results of NMT more accepted.

5. Conclusion

Female athletes demonstrate significant differences between their dominant and non-dominant side in tasks like tuck jump. These between limb asymmetries over 10% may be an indicative of over using of the takeoff leg (Sugiyama et al., 2014) or neuromuscular deficits (Ford et al., 2005; Myer et al., 2011).

When between-limb asymmetries (over 10%) are evident and undesirable, coaches will plan interventions to minimize these differences (Bishop et al., 2018), not only to achieve high performance, but also to prevent injury to the lower limbs (Sugiyama et al., 2014).

This study demonstrated that female athletes with between-limb asymmetries participated in this study had improvement in performance on single leg hop and single leg triple crossover hop tests, and the knee and hip muscles post intervention. It seems that the trunk and hip control NMT could be effective to improve the lower extremity strength and to obtain an appropriate muscle functional pattern in female athletes with inter limb asymmetry. Also, long term effectiveness of this study is needed to assure the effects of the training to prevent the ACL injury while landing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2019.04.014.

References

Avila, M. A., Brasileiro, J. S., & Salvini, T. F. (2008). Electrical stimulation and isokinetic training: Effects on strength and neuromuscular properties of healthy young adults. *Brazilian Journal of Physical Therapy, 12*, 435–440.

Baldon, M. R., Nakagawa, H. P. T., Muniz, B. T., Amorim, F. C., Maciel, D. C., & Serrao, V. F. (2009). Eccentric hip muscle function in females with and without patellofemoral pain syndrome. *Journal of Athletic Training, 44*, 490–496.

Barber-Westin, S. D., Hermeto, A. A., & Noyes, F. R. (2010). A six-week neuromuscular training program for competitive junior tennis players. *The Journal of Strength & Conditioning Research, 24*, 2372–2382.

Barber, S. D., Noyes, F. R., Mangine, R. E., McCloskey, J. W., & Hartman, W. (1990). Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clinical Orthopaedics and Related Research, 255*, 204–214.

Beynnon, B. D., & Fleming, B. C. (1998). Anterior cruciate ligament strain in-vivo: A review of previous work. *Journal of Biomechanics, 31*, 519–525.

Bishop, C., Read, A., Read, T., & Read, P. (2018). Training methods and considerations for practitioners to reduce inter-limb asymmetries. *Strength and Conditioning Journal, 40*(2), 40–46.

Brown, S. R., Feldman, E. R., Cross, M. R., Helms, E. R., Marrier, B., Samozino, P., et al. (2017 Nov 1). The potential for a targeted strength training program to decrease asymmetry and increase performance: A proof of concept in sprinting. *International Journal of Sports Physiology and Performance, 12*(10), 1392–1395. https://doi.org/10.1123/ijspp.2016-0590. Epub 2017 Dec 18.

Cvorovic, A. (2012). The influence of basketball on the asymmetry in the use of limbs. *Montenegro Journal of Sports Science and Medicine, 1*, 15–19.

Dello Iacono, A., Padulo, J., & Ayalon, M. (2016). Core stability training on lower limb balance strength. *Journal of Sports Sciences, 34*, 671–678.

Ford, K. R., Myer, G. D., Toms, H. E., & Hewett, T. E. (2005). Gender differences in the kinematics of unanticipated cutting in young athletes. *Medicine & Science in Sports & Exercise, 37*, 124–129.

Fort-Vanmeerhaeghe, A., Montalvo, A. M., Lloyd, R. S., Read, P., & Myer, G. D. (2017). Intra-and inter-rater reliability of the modified tuck jump assessment. *Journal of Sports Science and Medicine, 16*, 117–124.

Fort, Vanmeerhaeghe Azahara, Gual, Gabriel, Romero-Rodriguez, Daniel, & Unnitha, Viswanath (2016). Lower limb neuromuscular asymmetry in volleyball and basketball players. *Journal of Human Kinetics, 50*, 135–143.

Fousekis, K., Tsepis, E., & Vagenas, G. (2010). Lower limb strength in professional soccer players: Profile, asymmetry, and training age. *J sports Sci Med, 9*, 364.

Gonzalo-Skok, O., Tous-Fajardo, J., Suarez-Arrones, L., Arjol-Serrano, J. L., Casajus, J. A., & Mendez-Villanueva, A. (2017). Single-leg power output and between-limbs imbalances in team-sport players: Unilateral versus bilateral combined resistance training. *International Journal of Sports Physiology and Performance, 12*, 106–114.

Grindem, H., Logerstedt, D., Eitzen, I., Moksnes, H., Axe, M. J., Snyder-Mackler, L., et al. (2011). Single-legged hop tests as predictors of self-reported knee function in nonoperatively treated individuals with anterior cruciate ligament injury. *The American Journal of Sports Medicine, 39*, 2347–2354.

Hewett, T. E., Ford, K. R., Hoogenboom, B. J., & Myer, G. D. (2010). Understanding and preventing acl injuries: Current biomechanical and epidemiologic considerations-update. *N Am J Sports Phys Ther, 5*, 234.

Hewett, Timothy E., Myer, G. D., Kevin, R., Ford, Mark, Paterno, V., & Carmen, E. Quatman (2016). Mechanisms, prediction, and prevention of ACL injuries: Cut risk with three sharpened and validated tools. *Journal of Orthopaedic Research, 34*(11), 1843–1855.

Hopper, A. J., Haff, E. E., Joyce, C., Lloyd, R. S., & Haff, G. G. (2017). Neuromuscular training improves lower extremity biomechanics associated with knee injury during landing in 11–13year old female netball athletes: A randomized control study. *Frontiers in Physiology, 8*, 883.

Impellizzeri, F. M., Rampinini, E., Maffiuletti, N., & Marcora, S. M. (2007). A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Medicine & Science in Sports & Exercise, 39*, 2044–2050.

Lee, M., & Han, G. (2016). The effect of peculiar complex core balance training on isokinetic muscle functions of the knee and lumbus. *Journal of Physical Therapy, 28*, 1294–1297. Sc.

Lephart, S. M., Abt, J. P., Ferris, C. M., Sell, T. C., Nagai, T., & Myers, J. B. (2005). Neuromuscular and biomechanical characteristic changes in high school athletes: A plyometric versus basic resistance program. *British Journal of Sports Medicine, 39*, 932–938.

Letafatkar, A., Rajabi, R., Tekamejani, E. E., & Minoonejad, H. (2015). Effects of perturbation training on knee flexion angle and quadriceps to hamstring co-contraction of female athletes with quadriceps dominance deficit: Pre–post intervention study. *The Knee, 22*, 230–236.

Lindsay, D. M., Maitland, M. E., Lowe, R. C., & Kane, T. J. (1992). Comparison of isokinetic internal and external rotation torque using different testing position. *Journal of Orthopaedic & Sports Physical Therapy, 16*, 4 3–50.

Mandelbaum, B. R., Silvers, H. J., Watanabe, D. S., et al. (2005). Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *The American Journal of Sports Medicine, 33*, 1003–1010.

McGratha, T. M., Waddingtona, G., Scarvellab, J. M., Balla, N. B., Creerc, R., Woodsd, K., et al. (2016). The effect of limb dominance on lower limb functional performance- a systematic review. *Journal of Sports Sciences, 34*(4), 289–302.

Myer, G. D., Brent, J. L., & Hewett, T. E. (2011). Real-time assessment and neuro-muscular training feedback techniques to prevent ACL injury in female athletes. *Strength and Conditioning Journal, 33*(3), 21—35.

Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Rationale and clinical techniques for ACL injury prevention among female athletes. *Journal of Athletic Training, 39*, 352—364.

Myer, G. D., Ford, K. R., & Hewett, T. E. (2008). Tuck jump assessment for reducing anterior cruciate ligament injury risk. *Athletic Therapy Today, 13*, 39—44.

Noyes, F. R., Barber, S. D., & Mangine, R. E. (1991). Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *The American Journal of Sports Medicine, 19*, 513—518.

Portney, L. G., & Watkins, M. P. (2009). *Foundations of clinical research: Applications to practice* (3rd ed.). Upper Saddle River, NJ: Pearson Education.

Powell, J. W., & Barber-Foss, K. D. (2000). Sex related injury patterns among selected high school sports. *The American Journal of Sports Medicine, 28*, 385—391.

Rahimi, Z., Alizadeh, M. H., Nouri, R., & Rojhani, Z. (2014). The effect of neuro-muscular, strength and combined trainings on hamstring to quadriceps muscle strength ratio in female basketball players. *J ZUMS, 22*, 12—23.

Read, P. J., Oliver, J. L., De Ste Croix, M. B. A., Myer, G. D., & Lloyd, R. S. (2016). Neuromuscular risk factors for knee and ankle ligament injuries in male youth soccer players. *Sports Medicine, 46*(8), 1059—1066.

Rohman, E., Steubs, J., & Tompkins, M. (2015). Changes in involved and uninvolved limb function during rehabilitation after anterior cruciate ligament recon-struction: Implications for limb symmetry index measures. *The American Jour-nal of Sports Medicine, 43*, 1391—1398.

Rohman, E., & Tompkins, M. (2014). Changes in the uninvolved limb during reha-bilitation following ACL reconstruction, and recommendations for a practical and evidence-based functional testing battery. *Journal of Yoga & Physical Ther-apy, 5*, 3.

Sannicandro, I., Cofano, G., Rosa, R. A., & Piccinno, A. (2014). Balance training ex-ercises decrease lower-limb strength asymmetry in young tennis players.

Journal of Sports Science and Medicine, 13, 397—402.

Singh, A., Boyat, A. K., & Sandhu, J. A. (2015). Effect of six-week plyometric training on agility, vertical jump height and peak torque ratio of Indian taekwondo Players. *Medicine & Science in Sports & Exercise, 1*, 42—46.

Stockel, T., & weigelt, M. (2007). Bilateral competence and the level of competitive play — a study in basketball. 12th Annual Congress of the ECSS, 11-14 July 2007. *J. Finland*.

Sueyoshi, T., Nakahata, A., Emoto, G., & Yuasa, T. (2010). Original research. Single-leg hop test performance and isokinetic knee strength after anterior cruciate lig-ament reconstruction in athletes investigation performed at emoto knee and sport clinic, Fukuoka, Japan. *J Sports Physical Ther, 5*(4), 234—251.

Sugiyama, T., Kameda, Mai, Kageyama, Masahiro, Kiba, Kazufusa, Kanehisa, Hiroaki, & Maeda, Akira (2014). Asymmetry between the dominant and non-dominant legs in the kinematics of the lower extremities during a running single leg jump in collegiate basketball players. *Journal of Sports Science and Medicine, 13*, 951—957. http://www.jssm.org.

Taylor, B. J., Ford, R. K., Schmitz, J. R., Ross, E. S., Ackerman, A. T., & Shultz, J. S. (2018). A 6-week warm-up injury prevention program results in minimal biome-chanical changes during jump landings: A randomized controlled trial. *Knee Surgery, Sports Traumatology, Arthroscopy, 26*(10), 2942—2951.

Taylor, J. B., Ford, K. R., Schmitz, R. J., Ross, S. E., Ackerman, T. A., & Shultz, S. J. (2018). A 6-week warm-up injury prevention programme results in minimal biome-chanical changes during jump landings: A randomized controlled trial. *Knee Surgery, Sports Traumatology, Arthroscopy, 16*, 1—10.

Vaisman, A., Guiloff, R., Rojas, J., Delgado, I., Figueroa, D., & Calvo, R. (2017). Lower limb symmetry comparison of muscular power between dominant and nondominant legs in healthy young adults associated with single-leg-dominant sports. *Orthop J Sports Med, 5*(12).

Zahradnik, D., Jandacka, D., Uchytil, J., Farana, R., & Hamill, J. (2015). Lower ex-tremity mechanics during landing after a volleyball block as a risk factor for anterior cruciate ligament injury. *Physical Therapy in Sport, 16*, 53—58.