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Research article

# Effects of neuromuscular training on dynamic balance ability in athletes: A systematic review and meta-analysis

Peiling Wang [a], Yongfu Liu [b], Chao Chen [c,*]

[a] Macau University of Science and Technology, Macao, 999078, China
[b] School of Athletic Performance, Shanghai University of Sport, Shang Hai, 200438, China
[c] College of Physical Education, Dalian University, Dalian, 116622, China

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ABSTRACT

*Objectives:* This study aimed to quantitatively analyze the effects of neuromuscular training (NMT) on dynamic balance in healthy athletes through a systematic review and meta-analysis of randomized controlled trials.
*Methods:* Searches on six databases for randomized controlled trials examining the impact of NMT on athletes' balance ability. The search period extended from the inception of the database to March 16, 2024, languages are limited to Chinese and English. Review Manager 5.1 was used for literature quality assessment and data analysis. Stata 15.0 software was used for assessing publication bias, employing the clipping method, and conducting sensitivity analysis. The Grading of recommendations assessment development and evaluation (GRADE) was used to assess the certainty of evidence. Effect size (ES) was used to evaluate the impact effect of the results.
*Results:* (1) Meta-analysis: A total of 7 papers met the inclusion criteria, and the meta-analysis indicated that NMT had a positive impact on the dynamic balance ability of the right (SMD = 0.74) and left (SMD = 0.70) lower limb of athletes, and a statistically significant difference was observed ($p < 0.01$). Subgroup analysis revealed that NMT did not have a positive effect ($p > 0.05$) on the right anterior (SMD = 0.35); However, it had a positive effect ($p < 0.05$) on the right posteromedial (SMD = 1.22), right posterolateral (SMD = 0.82), right composite score (SMD = 0.79), left anterior (SMD = 0.38), left posteromedial (SMD = 1.19), left posterolateral (SMD = 0.57) and left composite score (SMD = 0.86). (2) Reporting bias: Funnel plot indicated evidence of publication bias, but there was no significant asymmetry in the funnel plot after trimming and filling. The results were not reversed, indicating the robustness of the combined results. (3) Sensitivity analysis: The results of the sensitivity analysis suggest that the data in this meta-analysis are relatively stable and credible. (4) Grading the evidence: Based on GRADE scale the certainty of evidence from the included studies was determined to be moderate.
*Conclusion:* Neuromuscular training can enhance the dynamic balance ability of athletes on both the left and right sides. Therefore, neuromuscular training is an effective method for enhancing the unilateral dynamic balance ability of athletes.

* Corresponding author.
*E-mail addresses:* 1356016425@qq.com (P. Wang), 2537818008@qq.com (Y. Liu), taishanchenchao@126.com (C. Chen).

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**Table 1**
Inclusion and exclusion criteria.

| Project | Inclusion criteria | Exclusion criteria |
|---|---|---|
| P | Athletes (Trained/developmental, Highly Trained/National) with no injuries, illnesses, or other clinical symptoms | Non-athletes;<br>Athletes (Recreationally Active Elite/International, World Class) with injuries, illnesses, or other clinical symptoms |
| I | NMT | Cognitive-Based Neuromuscular Training, CoBAgi training |
| C | special training, regular physical training | Other training, neuromuscular training combined with other training (It is not clear whether neuromuscular training or other training is responsible for the results.) |
| O | SEBT, YBT | Inconsistent indicators: center of pressure, single-limb postural stability, flamingo test, balance index, inertial measurement units<br>Means and standard deviations before and after the intervention were not available or reported |
| S | Randomized controlled trial | self-controlled trial, case analysis |

## 1. Introduction

The 2024 ACSM worldwide fitness trends indicate that developing muscular strength and power, as well as improving balance and proprioception, are essential for all individuals [1]. These improvements are inseparable from neuromuscular control. Neuromuscular control refers to the ability to maintain stability in the body's center of gravity [2]. Among them, nerves assess body posture and balance through sensory information and internal models, and generate appropriate neural commands to adjust muscle activity. Muscles initiate contractions through nerve impulses, generating forces and torques that create control forces around the joints to maintain stable posture and control the body's center of gravity [3]. Neuromuscular control plays a crucial role in influencing athletes' balance ability, which is essential for enhancing athletic performance and reducing the risk of sports injuries [2]. It encompasses both static and dynamic balance abilities [4,5]. Among these abilities, dynamic balance can help athletes maintain body stability and reduce the risk of injury (e.g. risk of falls and sprains, risk of muscle strains, etc.) during high-speed sports and strenuous activities [6]. The Star Excursion Balance Test (SEBT) and Y-Balance Test (YBT) are two widely used tests for assessing dynamic balance and motor control [7]. During these tests, the athlete tried to reach as far as possible with the opposite limb while maintaining a one-legged stance. The anterior, posteromedial, posterolateral, and composite score components of the YBT and SEBT were utilized to assess neuromuscular characteristics, including lower extremity coordination, balance, flexibility, and strength [8].

Neuromuscular training (NMT) is defined as a conceptual training program [9] that incorporates general (e.g., fundamental movements) and specific strength and conditioning tasks (e.g., resistance, balance, agility, plyometric) with the aim of preventing injuries, enhancing injury resilience, and improving sporting and motor skill performance [10,11]. At present, there is another development and extension of NMT — Integrative neuromuscular training (INT). Both NMT and INT emphasize the coordination of the nervous and muscular systems by increasing nerve conduction velocity, improving muscle contraction, enhancing sensory feedback to improve dynamic joint stability, enhancing motor patterns and skills, enhancing neuromuscular control, and enhancing strength [12,13]. Therefore, the two training methods are uniformly referred to as NMT in this study. NMT combine strength, speed, ultra-length and balance training together with typical functional training [14], and have been shown to improve multiple aspects of physical performance in athletes in many sports [15], such as basketball and football, including strength [16], power [17], balance [18], and speed [17].

Previous studies have conducted meta-analyses on NMT for sports injury recovery [19] (e.g., anterior cruciate ligament and ankle sprains), sports injury prevention [20–22], muscle strength [16], and change of direction [23]. No meta-analysis has been conducted to explore the effects of NMT on balance. Although some studies have investigated the effect of NMT on the balance ability of athletes, the results are inconsistent [24–26]. Therefore, this systematic review, combined with meta-analysis, aims to quantitatively analyze the effects of NMT on the dynamic balance ability of athletes and provide reference value for the application of neuromuscular training in sports training.

## 2. Information and research methods

The present systematic review and meta-analysis followed the PRISMA guidelines, and the protocol has been registered in PROSPERO (ID: CRD42024524275).

### *2.1. Study selection*

This meta-analysis followed the Cochrane Collaboration [27] and adhered to the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [28]. The PICOS methodology (population, intervention, comparator, outcome, study design) was applied as follows: (P) inclusion of athletes (Trained/developmental, Highly Trained/National) with no injuries, illnesses, or other clinical symptoms; (I) implementation of neuromuscular training or neuromuscular training-based warm-up; (C) comparison with special training, regular physical training; (O) assessment of dynamic balance before and after the intervention; (S) inclusion of randomized controlled trials. Specific inclusion and exclusion criteria are outlined in Table 1.

**Table 2**
The filters for each database.

| Database | Algorithm | Language |
|---|---|---|
| Web of Science | Topic | English |
| PubMed | Title/Abstract | English |
| ScienceDirect | Title/abstract/author-specified keywords | – |
| Scopus | TITLE-ABS-KEY | English, Chinese |
| CNKI | Topic | English, Chinese |

#1:TS = ("balance" OR "equilibrium" OR "balancing" OR "OR "balanced" OR "equilibrated" OR "equilibrium" OR "equalize" OR "balance ability" OR "balance capacity"

#2:TS = ("neuromuscular training" OR "neuromuscular exercise” OR “neuromuscular rehabilitation" OR "neuromuscular intervention" OR "neuromuscular conditioning" OR "integrative neuromuscular training" OR "INT" OR "NMT")

#3: TS = ("athlete" OR "players" OR "sports man" OR "player")

#4: #1 AND #2 AND #3

**Fig. 1.** Web of science literature selection strategy.

### *2.2. Search strategy*

The present systematic review and meta-analysis conducted searches in databases such as PubMed, Web of Science, Scopus, ScienceDirect, and China National Knowledge Infrastructure (CNKI) (Table 2). The search time frame extended from the inception of records in each database to March 16, 2024, languages are limited to Chinese and English.

The search process is illustrated in Fig. 1 (Web of Science was used as an example). To ensure the accuracy of the search, two researchers cross-checked the search keywords. If there were any disagreements on keyword selection between the two researchers, a third researcher would make the final decision. If necessary, manual searches will be conducted to supplement the literature.

### *2.3. Data extraction*

Two researchers searched each database using the same search formula and utilized Google Translation to independently translate and read the titles and abstracts for preliminary screening. After screening the literature in each database, it was imported into EndNote X9 software for sorting. Additionally, two researchers utilized Google Translation to review the full text and determine which literature met the inclusion and exclusion criteria. The literature screening process was conducted independently by two researchers, and any disputes that arose were resolved by a third researcher.

After confirming the final inclusion of all literature in the analysis, two researchers extracted the data into a Microsoft Excel spreadsheet. The extracted data included the article title, year of publication, author(s) name, subject characteristics (e.g., age, number of participants in the experimental and control groups, training protocol, period, outcome, results), training regimen (intervention period, training frequency, duration, intervention means for experimental and control groups), and pre- and post-test data for outcome indicators (YBT and SEBT). The pre- and post-test data are as mean ± standard deviation, and all data are available from text and tables. If the data extracted by the two researchers was biased, it was reviewed and finalized by a third researcher. If the full text or study data could not be accessed, the authors of the literature were contacted via email for the content.

### *2.4. Assessment of risk of bias*

The Cochrane Risk of Bias Tool in Review Manager software version 5.4 was used by two independent researchers to assess the methodological quality of each eligible randomized controlled trial (RCT). The included studies were scored for risk of bias along seven dimensions: 1) random sequence generation, 2) allocation concealment, 3) blinding of participants and personnel, 4) blinding of outcome assessment, 5) incomplete outcome data, 6) selective reporting, and 7) other bias. The assessment employed the criteria of ‘Low risk’, ‘Unclear risk’, and ‘High risk’ (≥4: Low, 2–3: Unclear, and 0–1: High). The final results formed the basis for evaluating the quality of the literature.

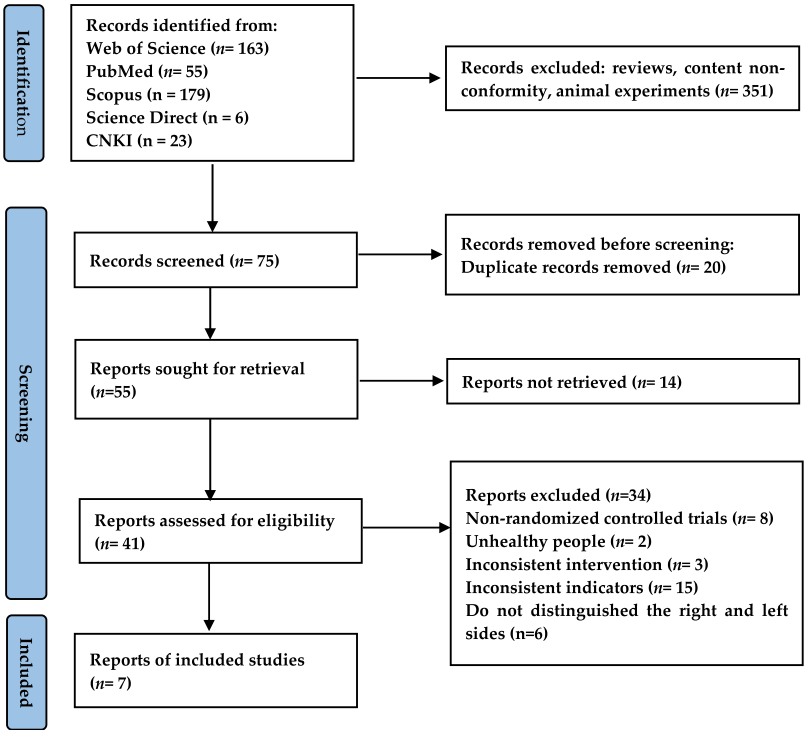


**Fig. 2.** PRISMA flow chart for inclusion and exclusion of studies.

### 2.5. Statistical analysis

Data were analyzed using Review Manager software version 5.4 and Stata 15.0. The standardized mean difference (SMD) with 95 % confidence intervals (CI) was utilized as the combined effect indicator for continuous outcome variables. $I^2$ was used to evaluate the heterogeneity of the studies and was considered insignificant (0 %~25 %), moderate (25 %~75 %) or high (75 %~100 %) [29]. If $I^2 <$ 25 %, the fixed-effects model was used to analyze the outcome indicators. Otherwise, a random effects model was used. $P < 0.05$ was deemed statistically significant. Effect sizes (ES) were classified according to Cohen's *d* index as small ($0.2 \leq ES < 0.5$), medium ($0.5 \leq ES < 0.8$) or large ($ES \geq 0.8$). The Cochrane Risk of Bias Tool was utilized to evaluate the quality of the studies that met the inclusion criteria to ascertain their internal and external validity. Subgroup analyses were conducted using within-study contrasts to investigate the influence of results in various directions on the final outcomes. The funnel plot and Egger's regression were used to assess the publication bias of the included studies. When publication bias was present in the included studies, Duval and Tweedie's trim-and-fill procedure was utilized to adjust the funnel plot, and the publication bias was assessed post-adjustment. Sensitivity analysis was conducted to assess the robustness and reliability of the aggregated findings from the meta-analysis. The certainty of the body of evidence was assessed using Grading of Recommendations Assessment, Development and Evaluation (GRADE).

## 3. Results

### 3.1. Literature search

A total of 426 studies were retrieved (Fig. 1). Based on the information in the title and abstract, 75 citations were left for removing duplicate. After removing duplicate citations, 55 studies remained for full-text screening. After full-text screening, eight studies were non-randomized controlled trials and were therefore excluded [21,22,30–35]. The subjects in these two studies were injured athletes; therefore, these two studies were excluded [36,37]. Three studies were excluded because they did not meet the established definitions of intervention [38–40]. A total of 15 studies were excluded because the outcome measures did not meet the inclusion criteria [15,41–54], and 6 studies were excluded because YBT or SBRT tests were performed to differentiate between the left and right legs [55–60]. Finally, 7 articles, meeting the eligibility criteria, were included for further analysis [8,24–26,61–63].

### 3.2. Study characteristics

A total of 7 studies [8,24–26,61–63] involving 376 athletes were ultimately included in this paper, as they met the inclusion criteria for the analysis. The detailed inclusion and exclusion process is illustrated in Fig. 2 below. The experimental group (N = 200) received

**Table 3**
Summary of reviewed studies including study design, level of evidence, period, outcome and result.

| Studies | Participants | INT protocols | CON protocols | Period | Outcome | Result |
|---|---|---|---|---|---|---|
| Benis 2016 [8] | Female basketball players N (NMT) = 14 N (CON) = 14 Age = 20 ± 2 | NMT research focuses on core stability and plyometrics, and the actions involved include: plank on elbows, side bridge, one-leg hip lift, split squat, front lunges, two-legged calf raise on step, abdominal crunches, lateral jump and hold, back hyperextension on ground, and tuck jump and soft landing | Light aerobic exercises, basketball and team drills, and dynamic stretching of the major muscle groups before the regular practice sessions | 8 weeks 2 per week 30 min | YBT ①②③④ | 1.Improvement over baseline scores was noted in the posteromedial and posterolateral reach directions and in the composite scores of the NMT. 2.No differences in anterior reach were detected in either group ($p > 0.05$). 3.Differences were noted in postintervention scores for posteromedial reach and composite scores between the NMT and CON. |
| Bonato 2018 [26] | Female basketball players N (NMT) = 86 N (CON) = 74 Age = 20 ± 2 | NMT main focus of training was to improve awareness and neuromuscular control during standing, running, planting, cutting, jumping, and landing. Including 5 parts: running exercises at low speed with the ball, 7 exercises of active stretching, 4 exercises focused on general strength, 4 sets of plyometric, balance, and jumping exercising, speed running combined with basketball movements with sudden changes of direction. | Light aerobic exercises, basketball and team drills, and dynamic stretching of the major muscle groups before the regular practice sessions | 28 weeks 4 per week 30 min | YBT ① | 1.NMT showed significant improvement in composite scores ($p < 0.05$). 2.Significant differences in post-intervention composite scores between the NMT and the CON were observed ($p < 0.05$). |
| Hopper 2017 [62] | Female basketball players N (NMT) = 13 N (CON) = 10 Age = 12.17 ± 0.94 | Plyometric exercises, strength training, and the strength training sections used barbells, medicine balls, and resistance bands. Actions include: ½ squat, lateral bound with stick, single leg push off (low box), 90° spin jump, back squat, medicine ball static lunge (bent arms), military press, horizontal pull-up (knees bent). | Normal netball training and games | 6 weeks 3 per week 60 min | SEBT ②③④ | NMT only demonstrated increased reach in the anterior and posteromedial directions for the right leg and left leg, and in the posterolateral direction for the left leg. |
| Lindblom 2012 [24] | Female football players N (NMT) = 23 N (CON) = 18 Age = 14.2 ± 1.1 | Targeting core stability, balance, landing technique, and proper knee alignment. The exercises are as follows: one-legged knee squat, pelvic lift, two-legged knee squat, the bench, the lunge, and jump/landing. | Usual football training | 11 weeks 2 per week 15 min | SEBT ②③④ | No significant effect of the intervention was found for any of the performance measures ($p > 0.05$). |
| O'Malley 2017 [25] | Male football and hurleys players N (NMT) = 41 N (CON) = 37 Age = 18.6 ± 0.4 | The focus of the intervention was to develop neuromuscular control in bilateral and unilateral lower-limb activities, develop muscular strength and activation, and develop improved jump-landing techniques (to land in positions of hip, knee, and ankle stability and increasing hip and knee flexion) to decrease landing forces. | Usual football training | 8 weeks 2 per week 15 min | YBT ①②③④ | NMT showed Moderate effect sizes in favor for right (d = 0.59) and left (d = 0.69) composite scores, with adjusted mean differences between NMT and CON for right and left legs ($p < 0.01$). |
| Vitale 2018 [61] | Male skiing players N (NMT) = 12 N (CON) = 12 Age = 18 ± 1 | NMT focus on the quality of the movement and put emphasis on core stability, hip control, and proper knee alignment. The main focus of training was to improve awareness and neuromuscular control during standing, running, planting, cutting, jumping, and landing. Actions include: plank on elbows, side bridge, one-leg hip lift, split squat, front lunges, two-legged calf raise on step, abdominal | Light aerobic exercises and dynamic stretching of the major muscle groups before the regular practice sessions | 8 weeks 2 per week 30 min | YBT ① | NMT achieved positive effects from pre to post measures in the anterior, posteromedial, posterolateral, and composite score for both lower limbs, whereas no significant differences were detected for CON ($p < 0.05$). |

(continued on next page)

**Table 3** (*continued*)

| Studies | Participants | INT protocols | CON protocols | Period | Outcome | Result |
|---|---|---|---|---|---|---|
| | | crunches, lateral jump and hold, back hyperextension on ground, and tuck jump and soft landing. | | | | |
| Hang 2023 [63] | Female basketball players<br>N (NMT) = 11<br>N (CON) = 11<br>Age = 20 ± 2 | The training schedule consisted of two parts, core stability training and plyometric training. | rope skipping × 4, push-up × 4, five full speed runs, strength training | 8 weeks<br>3 per week<br>30 min | YBT<br>②③④ | NMT had significant improvements anterior, posteromedial, posterolateral and composite score ($p < 0.05$). |

Note: NMT, Neuromuscular training; CON, Control; Y, Y-balance; SEBT, Star excursion balance test; ①, Composite score; ②, Posterolateral; ③, Posteromedial; ④, Anterior.

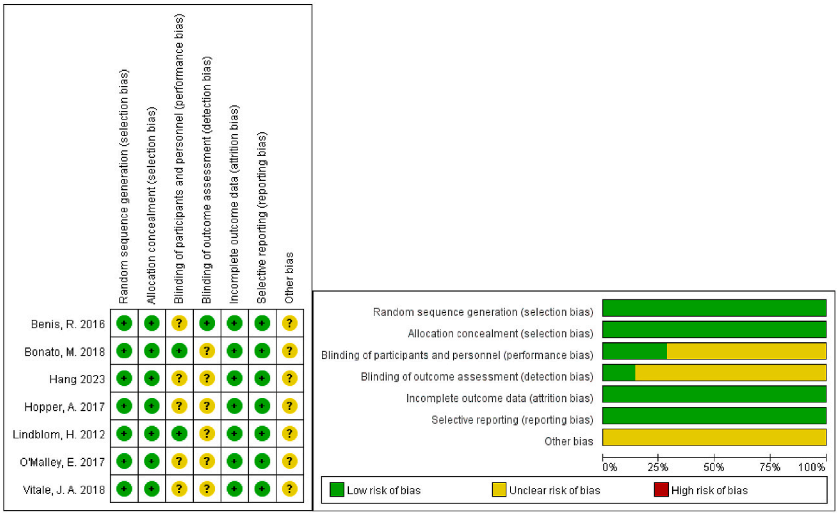


**Fig. 3.** Risk of bias assessment chart.

neuromuscular training, while the control group (N = 176) only underwent routine training without any additional intervention. In the studies included, the sample size ranged from 10 to 86. The intervention period in the included studies varied from 6 to 28 weeks, the frequency of intervention ranged from 2 to 4 times per week, and the duration of each intervention varied from 15 to 60 min (Table 3).

### *3.3. Risk of bias in the included articles*

The Cochrane Risk of Bias assessment tool was utilized to evaluate the quality of all the literature included in this meta-analysis. All the studies included in this analysis were randomized controlled trials. Seven studies reported allocation concealment, and two studies implemented blinding of the researchers and participants. All the studies included in this meta-analysis were rated as having a low risk of bias (Fig. 3).

### *3.4. Meta-analysis results*

The impact of neuromuscular training on right limb dynamic balance ability.

A total of 7 studies, comprising 20 experimental groups and 866 participants, were included in this meta-analysis to assess the effect of NMT on athletes' anterior thigh dynamic balance ability (Fig. 4). Overall, the effect sizes indicate that NMT has a significant impact on athletes' dynamic balance ability in their right limb [SMD = 0.75, 95 % CI (0.42, 1.08)], with high heterogeneity ($I^2 = 80.5$ %) and statistical significance ($P < 0.01$). Subgroup analysis revealed that NMT had no significant effect on the dynamic balance ability of the right anterior [SMD = 0.35, 95 % CI (−0.03, 0.72), P = 0.19, $I^2 = 34.3$ %]. However, it had a significant effect on the dynamic balance ability of the right posteromedial [SMD = 1.22, 95 % CI (0.18, 2.25), P = 0.00, $I^2 = 89.2$ %] and right posterolateral [SMD = 0.82, 95 % CI (−0.04, 1.68), P = 0.00, $I^2 = 85.6$ %], as well as on the right composite score [SMD = 0.79, 95 % CI (0.17, 1,41), P = 0.00, $I^2 = 82.7$ %].

The impact of neuromuscular training on left limb dynamic balance ability.

A total of 7 studies, comprising 20 experimental groups and 866 participants, were included in this meta-analysis to assess the effect of NMT on athletes' anterior thigh dynamic balance ability (Fig. 5). Overall, the effect sizes indicate that NMT has a significant impact

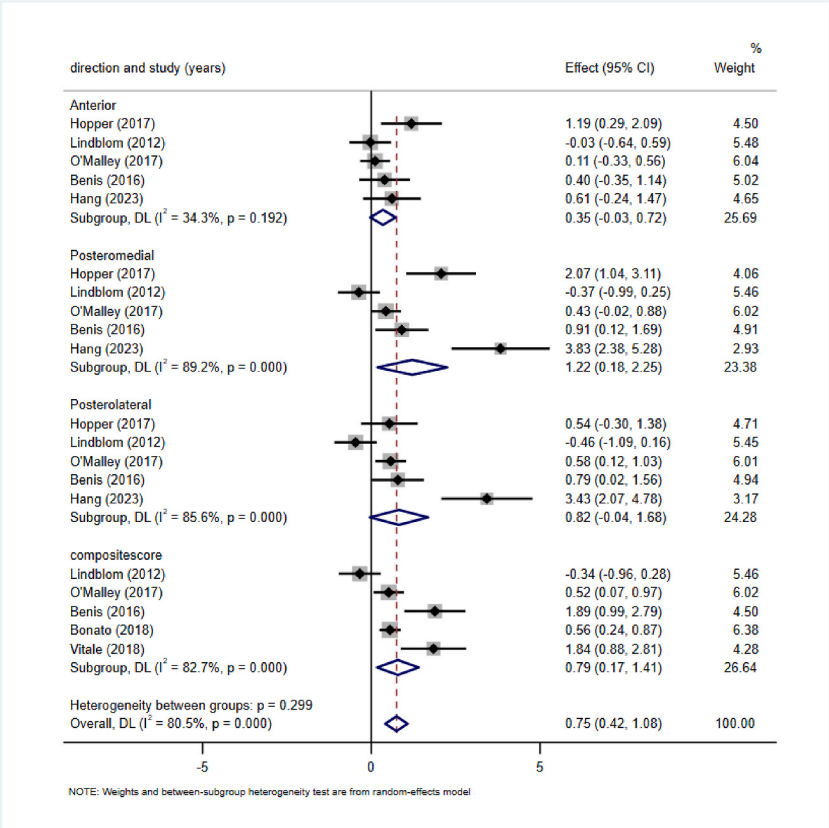


**Fig. 4.** Forest plot of the effect of neuromuscular training on right limb dynamic balance ability.

on athletes' dynamic balance ability in their left limb [SMD = 0.70, 95 % CI (0.36, 1.05)], with high heterogeneity ($I^2$ = 82 %) and statistical significance (P < 0.01). Subgroup analysis revealed that NMT had significant effect on the dynamic balance ability of the left anterior [SMD = 0.38, 95 % CI (−0.17, 0.92), P = 0.02, $I^2$ = 67.6 %], left posteromedial [SMD = 1.19, 95 % CI (0.12, 2.26), P = 0.00, $I^2$ = 89.9 %], left posterolateral [SMD = 0.57, 95 % CI (−0.07, 1.21), P = 0.00, $I^2$ = 76.2 %], and left composite score [SMD = 0.86, 95 % CI (0.10, 1.61), P = 0.00, $I^2$ = 88.2 %].

### 3.5. Reporting bias

Visual inspection of the funnel plot (Fig. 6) showed evidence for publication bias. Distribution of effect sizes was asymmetry. For both left and right dynamic balance abilities, half of the effect values fall within the funnel, while asymmetric effect sizes are observed outside the funnel. Egger's regression test showed significant results on the right ($p = 0.010$) and left ($p = 0.023$) sides, respectively. As with the funnel plot, the presence of publication bias is also indicated.

It was found that a total of 7 studies were missing (Fig. 7), with 4 items missing in the right dynamic balance ability and 3 items missing in the left dynamic balance ability. The random-effects model was utilized for the meta-analysis on the right (Q = 97.22, P = 0.00), yielding a combined effect index of 0.75 (95 % CI: 0.42–1.08). The linear method was used to estimate that there were 4 missing studies after 4 iterations (final diff = 0). After imputation of missing studies, the meta-analysis result was Q = 161.34, P = 0.00, and the combined result of the random-effects model was 1.52 (95 % CI: 1.05–2.21). The random-effects model was utilized for the meta-analysis on the left side (Q = 105.83, p = 0.00), and the combined effect index of the random-effects model was 0.71 (95 % CI: 0.36–1.05). The linear method was used to estimate that the number of missing studies was 2 after three iterations (final diff = 0). After including the missing studies, the meta-analysis yielded a Q value of 137.90 with a P value of 0.00. The combined result from the random-effects model was 1.71 (95 % CI: 1.18–2.46). There was no significant asymmetry in the funnel plot after trimming and filling, and the results were not reversed, indicating the robustness of the combined results.

### 3.6. Sensitivity analysis

A sensitivity analysis was conducted using Stata 17.0 to assess the potential impact of each study on the outcome of the meta-analysis (Fig. 8). The results of the sensitivity test of neuromuscular training on right limb dynamic balance ability fluctuate around 0.75, while the results of the sensitivity test of neuromuscular training on left limb dynamic balance ability fluctuate around

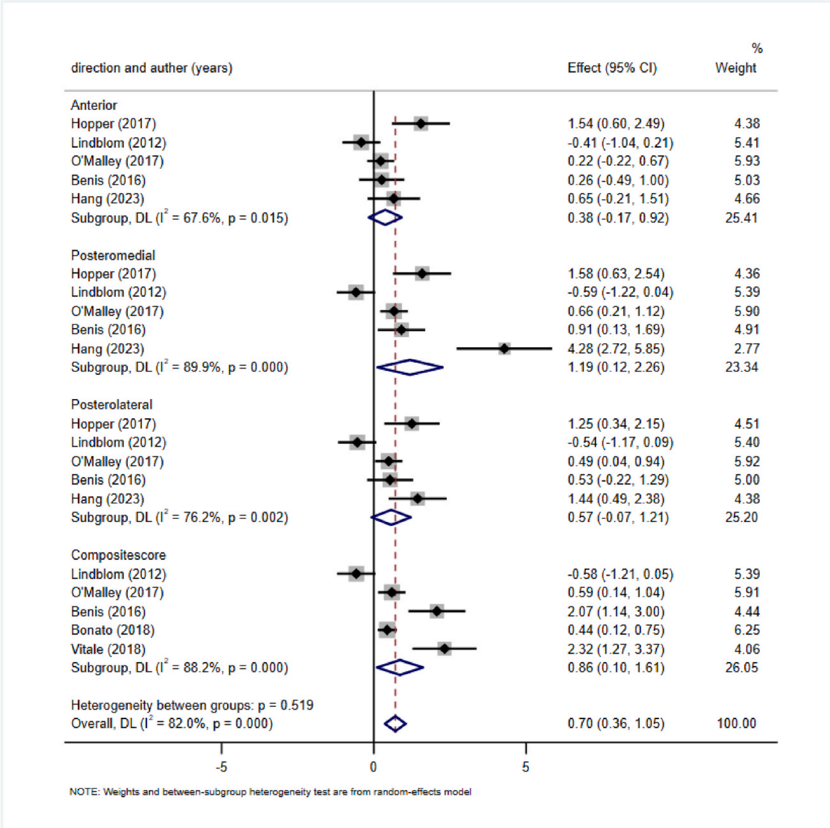


**Fig. 5.** Forest plot of the effect of neuromuscular training on left limb dynamic balance ability.

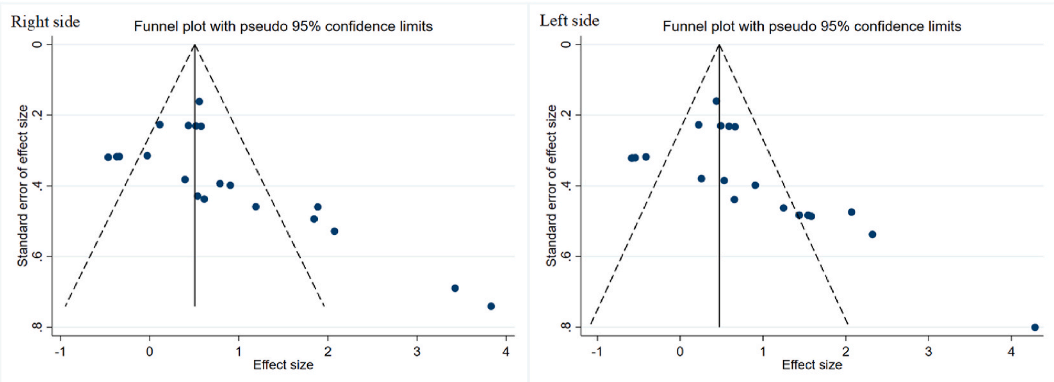


**Fig. 6.** Funnel plot of the effect of neuromuscular training on dynamic balance ability.

0.70. The results of the sensitivity analysis suggest that the data in this meta-analysis are relatively stable and credible.

### *3.7. Grading the evidence*

Based on the grading analysis, the certainty of evidence from the included studies was determined to be moderate because the risks of bias, indirectness, and imprecision were highly graded, while inconsistency and publication bias were graded as low (Table 4).

## 4. Discussion

The purpose of this meta-analysis was to evaluate the effect of NMT on dynamic balance in athletes. Although NMT did not

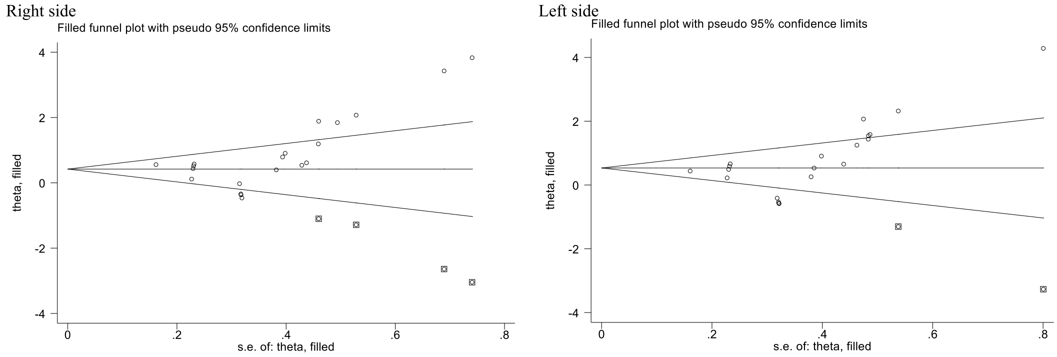


**Fig. 7.** Funnel plot of the effect of neuromuscular training on dynamic balance ability after trim and fill.

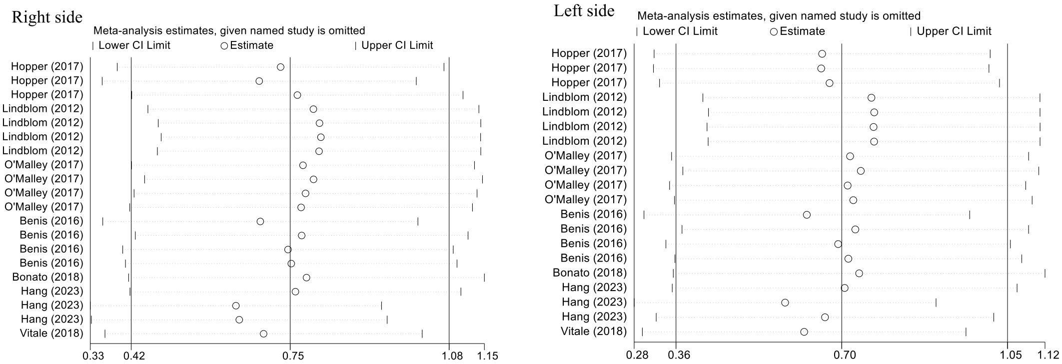


**Fig. 8.** Sensitivity analysis of the effect of neuromuscular training on dynamic balance ability.

significantly improve the anterior extension distance of the right limbs, it had a positive impact on the overall score of the bilateral limbs and the extension distance of the bilateral limbs in other directions. Therefore, we believe that NMT is an effective approach for improving the dynamic balance ability of athletes. This also supports the previous idea that NMT can improve dynamic balance [8,34].

Dynamic balance is considered a crucial factor that influences athletic performance, as it allows athletes to maintain a stable center of gravity when executing specific technical movements [64,65]. The enhancement in the extension distance of both limbs in various directions through NMT may be attributed to improved neuromuscular control and dynamic balance [66,67]. NMT is defined as a comprehensive training program that integrates fundamental movements and specific training tasks, including resistance, balance, agility, and plyometric [10,11]. Core stability training, plyometric training, and balance training were the primary methods of neuromuscular training included in this study. Among them, core stability is crucial for athletes as it enables them to maintain control of the torso on the pelvis and effectively generate and manage power in the extremities during exercise [66]. Core stability training has been shown to enhance trunk muscle strength, Y balance test performance, and the maximum extension distance on SEBT [68,69]. Core stability training not only strengthens the core muscle groups but also enhances the trunk's ability to control the end of the movement chain. Plyometric training involves elongation-shortening cycles, the storage of energy during the eccentric loading phase, and the stimulation of muscle spindles to maximize energy production during the concentric phase of exercise [70,71]. Studies have found that plyometric training can enhance muscle strength, speed, and agility [70,72]. Balance training has been shown to improve performance on balance-related tests [73–75]. Gandevia et al. [75]stated that balance training can improve proprioceptive feedback and facilitate quicker and more efficient neuromuscular activation during movement.

NMT integrates various training methods to facilitate adaptive changes in the nervous system by repeatedly stimulating the neuromuscular system [76,77]. Long-Term Potentiation (LTP) of the nervous system enhances the efficiency of synaptic transmission by repeatedly stimulating synapses. This process strengthens connections between neurons and improves the speed of neuromuscular responses. As a result, athletes can promptly and accurately respond to balance threats [78]. At the same time, it can enhance the efficiency of the neuromuscular junction, enabling the muscles to respond better to stretching actions and maintain balance and stability more effectively during the extension process [79]. The muscular system can increase its cross-sectional area, muscle fiber number, and protein synthesis through proper strength training, thereby enhancing strength [3]. Strong muscles can provide a more stable base of support, reduce the risk of balance imbalance, and enhance athletes' adaptability to changes in movement direction. Through coordination training, individuals can enhance their cooperative activities and control abilities, strengthen the efficiency of neuromuscular connections, improve muscle contribution to balance control, and enhance motor skills and movement fluency [80]. Overall, NMT may have a positive impact on athletes' dynamic balance ability by improving neuroadaptability, muscle strength, and

**Table 4**
GRADE evidence table for the effect of neuromuscular training on dynamic balance ability.

| Certainty assessment | | | | | | | № of patients | | Effect | | Certainty | Importance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| № of studies | Study design | Risk of bias | Inconsistency | Indirectness | Imprecision | Publication bias | [NMY] | [CON] | Relative (95 % CI) | Absolute (95 % CI) | | |
| **Right limb dynamic balance ability** | | | | | | | | | | | | |
| 20 | Randomized controlled trial | not serious | Serious[a] | Not serious | Not serious | Serious[c] | 459 | 407 | – | SMD 0.75 (0.42,1.08) | ⨁⨁⨁⊝⊝ Moderate | Important |
| **Left limb dynamic balance ability** | | | | | | | | | | | | |
| 20 | Randomized controlled trial | not serious | Serious[b] | Not serious | Not serious | Serious[d] | 459 | 407 | – | SMD 0.70 (0.36,1.05) | ⨁⨁⨁⊝⊝ Moderate | Important |

CI: confidence interval; MD: mean difference.
High certainty: we are very confident that the true effect lies close to that of the estimate of the effect.
Moderate certainty: we are moderately confident in the effect estimate; the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.
Low certainty: our confidence in the effect estimate is limited; the true effect may be substantially different from the estimate of the effect.
Very low certainty: we have very little confidence in the effect estimate; the true effect is likely to be substantially different from the estimate of effect.
[a] . Serious inconsistency since $I^2 = 80.5$ %. Downgrade.
[b] . Serious inconsistency since$^{I2} = 82$ %. Downgrade.
[c] . The funnel plot of 20 randomized trials indicated that 9 studies were beyond the funnel plot or on the border of the funnel plot. The certainty of the evidence was lowered.
[d] . The funnel plot of 20 randomized trials indicated that 8 studies were beyond the funnel plot or on the border of the funnel plot. The certainty of the evidence was lowered.

stability. These physiological changes may help improve the accuracy, efficiency, and stability of balance control, thereby enhancing athletes' ability to maintain balance in different movement directions.

In addition, we observed that there was no significant improvement in the forward extension distance of the right limb. The occurrence of this phenomenon may be due to the fact that the NMT included did not specifically target the practice of the ankle dorsiflexion range. However, the forward extension distance of the SEBT and YBT is related to ankle dorsiflexion, explaining 28 % of the forward extension performance [68]. Additionally, the left side (supporting leg) is the non-dominant side for most individuals, and the enhancement of the left limb is relatively minimal without targeted training. The modest improvement in the distance of the right forelimb may be a response to defects in the training protocol, but it did not affect our findings.

YBT, a validated adaptation of the SEBT, has been shown to be effective in identifying imbalances in homeostasis [81–83]. Poor performance on the YBT has been associated with an increased risk of non-contact lower extremity injurie [84]. Although we did not directly study the effect of NMT on lower extremity injuries, it can be speculated that NMT may help prevent lower extremity injuries. This is suggested by the improvement in YBT test performance. NMT can result in various biomechanical effects, including a reduction in ground force and abduction-adduction moments, and an increase in the hamstrings to quadriceps femoris ratio [83]. Some studies have indicated that the concurrent contraction of the hamstrings and quadriceps femoris can provide dynamic joint stability, thereby protecting the knee joint during exercise tasks [84]. It is evident that NMT are effective in preventing lower limb sports injuries. In daily training, coaches can integrate NMT into the program to prevent lower limb injuries, improve physical fitness, and prolong the athletic careers of athletes. In addition, NMT can be integrated into physical exercise training focused on functional and dynamic balance to improve muscle strength and limb coordination non-athletes, improve motor ability, postural control, and limb stability, and help reduce the risk of falls.

## 5. Limitations

Based on extensive experimental research on neuromuscular training for athletes, this study conducted an in-depth statistical analysis of how neuromuscular training affects dynamic balance ability. However, it is undeniable that the error caused by the heterogeneity of the results cannot be excluded from our comprehensive and accurate understanding of the effects of neuromuscular training. At the same time, there were relatively few experimental studies included in this meta-analysis, which could introduce errors into the research results. Therefore, we recognize the need for more extensive and accurate exploration of the effects of neuromuscular training on balance in athletes in the future.

## 6. Conclusion

Neuromuscular training can improve athletes' dynamic balance ability on both the left and right sides. Therefore, we believe that neuromuscular training is an effective approach for enhancing athletes' unilateral dynamic balance ability, even though the improvement may not be significant in the right anterior. The use of neuromuscular training to improve balance could be a valuable training method for athletes and coaches. However, it is essential to consider individual differences and training goals in order to develop personalized training programs.

## Ethical statement

None declared. This work does not require ethical approval.

## Data availability statement

The datasets used and/or analyst during the current study are available from the corresponding author on reasonable request.

## CRediT authorship contribution statement

**Peiling Wang:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Data curation. **Yongfu Liu:** Writing – original draft, Resources, Methodology, Data curation. **Chao Chen:** Validation, Supervision, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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