Effects of muscle electromyography analyses of unstable training on muscle activation: A Systematic Review and meta-analysis

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Abstract

Objective: To systematically evaluate the effects of unstable training (UT) on muscle activation and provide activation prescriptions for different muscle regions, offering more targeted guidance for different populations in muscle activation.

Methods: Data extraction and meta-analysis were conducted using RevManager5.3, Stata16.0, and R software. Subgroup analyses were performed on five variables: Exercise Equipment, exercise intensity, exercise mode, exercise experience, and contraction mode. Heterogeneity and publication bias were also examined.

Results: A total of 28 studies were included, involving 579 participants.Comparison of activation effects between unstable training and stable training: Significant increases in core muscle activation, including rectus abdominis (*SMD*=0.32, *95%CI*: 0.18-0.46, *P*<0.01), internal oblique (*SMD=0.38*, *95%CI*: 0.20-0.56, *P*<0.01), external oblique (*SMD*=0.38, *95%CI*: 0.20-0.56, *P*<0.01), and erector spinae (*SMD*=0.60, *95%CI*: 0.17-1.02, *P*<0.01); Significant increases in upper limb muscle activation, including biceps brachii (*SMD*=0.52, *95%CI*: 0.23-0.80, *P*<0.01), trapezius (*SMD*=0.23, *95%CI*: 0.12-0.35, *P*<0.01), serratus anterior (*SMD*=0.33, *95%CI*: 0.07-0.59, *P*=0.01), and triceps brachii (*SMD*=0.24, *95%CI*: 0.04-0.45, *P*=0.02); Significant increases in lower limb muscle activation, including soleus (*SMD*=0.65, *95%CI*: 0.42—0.87, *P*<0.01), gluteus medius (*SMD*=0.28, *95%CI*: 0.05—0.52, *P*=0.02).In subgroup analysis, the core muscles with the great effect were: rectus abdominis (Bosu ball, body weight, sit-ups), internal oblique (Swiss ball, relative load, bench press), external oblique (Swiss ball, body weight, sit-ups), erector spinae (TRX suspension, body weight, bridging); the upper limb muscles with the great effect were: biceps brachii (more than 1 year of training experience, TRX suspension, body weight, muscle-up), trapezius (less training experience, Bosu ball, body weight, push-ups), triceps brachii (body weight).The lower limb muscles with the great effect were: soleus (squats).Negative activation effects: erector spinae (Swiss ball, 60% 1RM load, and press movements), serratus anterior (Swiss ball), triceps brachii (more than one year of training experience, Swiss ball, >60% 1RM; rectus femoris (Bosu ball, squats).

Conclusion: Unstable training can significantly activate core, upper limb, and lower limb muscles.

Keywords: unstable training; muscle electromyography; muscle activation; activation prescription; Meta-analysis

1. Introduction

Unstable training (UT) refers to various strength and stability exercises performed on unstable surfaces, which enhance the activation of core and surrounding muscles by increasing the body's response to unstable conditions[1]. The degree of muscle activation varies under different environmental conditions [2]. When the external environment changes, proprioceptors in joints, tendons, and muscles become more sensitive to help the body perceive position and adjust posture [3]. Unstable training is frequently applied in rehabilitation training [4],[5],[6], as it enhances sensory feedback, challenges the coordination of muscles and the nervous system, thereby improving body stability and control, which is

Comentado [AB1]: Thank you for the opportunity to review your manuscript entitled *"Effects of Muscle Electromyography Analyses of Unstable Training on Muscle Activation: A Systematic Review and Meta-Analysis"*. This is an interesting and relevant study that systematically evaluates the effects of unstable training on muscle activation. The manuscript is well-structured and addresses an important topic in sports science. The authors should be commended for their effort in synthesizing the current evidence and providing practical applications for unstable training

Comentado [AB2R1]: With some minor revisions to address the areas for improvement outlined below, I believe the manuscript will be suitable for publication.

Comentado [AB3]: •Clearly states the objective, methodology, and key findings.
•The use of specific effect sizes and confidence intervals strengthens the reported results.

Comentado [AB4R3]: Consider briefly summarizing the limitations of the meta-analysis

Consider adding a sentence on the practical applications of the findings to highlight the relevance of the study.

Comentado [AB5]: •The introduction effectively defines unstable training and its relevance in rehabilitation and sports performance.
•The rationale for the study is well-presented, with a logical progression leading to the research question.

Comentado [AB6R5]: Consider adding a stronger theoretical foundation regarding the physiological mechanisms underlying unstable training's effects on muscle activation. While the introduction provides a good overview of UT, it could briefly discuss the potential mechanisms by which UT enhances muscle activation (e.g., proprioceptive feedback, neuromuscular adaptations).

Consider expanding on the practical applications of UT in different contexts (sports performance, rehabilitation etc) to further justify the study's significance.

crucial for promoting motor learning and neuroplasticity [7], particularly important for individuals with motor dysfunction.[1][2][3][4][6][7]

Muscle Activation plays a crucial role in athletic performance, directly influencing an athlete's strength, endurance, and movement efficiency, enabling them to optimize their performance in various sports activities [8]. Adequate muscle activation not only fully utilizes muscle strength and enhances the agility and responsiveness of the neuromuscular system but also reduces the risk of sports injuries, especially in movements involving multiple joints and complex actions, where the adequacy of muscle activation is even more critica [9],[10]. Therefore, when conducting sports training, it is essential to pay close attention to the state of muscle activation, particularly during compound movements, where muscle activation is most crucial. Among these, a deep understanding of the differences in muscle activation effects among various movements is a crucial foundation and necessary prerequisite for formulating appropriate exercise prescriptions [11], which helps to enhance training effectiveness and reduce injury risks, making sports training more scientific and targeted.[8]**Erro! A origem da referência não foi encontrada.**[9][10][11]

Previous studies on the activation of unstable cores have all held the attitude that they can change the activation effect. However, there are divergences in the activation of the upper and lower limbs. In the review by Batista GA etal [12], the effects of different surfaces on electromyographic activity were systematically evaluated, but the included studies showed high overall heterogeneity, few variables, and did not rigorously screen and group some key factors (such as training intensity, training time, subjects' physical fitness, and training experience), making it difficult to clearly distinguish the effects of different unstable training. Moreover, the indicators for subgroup analysis were incomplete, lacking detailed analysis, and providing limited reference value. Based on this, this study aims to analyze the intervention effects of unstable training on muscle activation in various parts, summarize more detailed muscle activation methods, and explore their intrinsic mechanisms, providing more targeted guidance for practical applications.[12]

2. Methods

This review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [107] and preregistered in the PROSPERO data: (ID:CRD42024600670)

2.1 Search strategy

Relevant literature was searched in databases such as CNKI, VIP, Wanfang, PubMed, EBSCOhost, and Web of Science, with the search time ranging from the establishment of each database to November 26, 2024.

The retrieval strategy takes PubMed database retrieval as an example, ("unstable"[Title/Abstract] OR "instability"[Title/Abstract] OR "surface"[Title/Abstract]) AND ("biceps brachii"[Title/Abstract] OR "trapezius"[Title/Abstract] OR "serratus anterior"[Title/Abstract] OR "triceps brachi"[Title/Abstract] OR "biceps brachii"[Title/Abstract] OR "trapezius"[Title/Abstract] OR "anterior deltoid"[Title/Abstract] OR "posterior deltoid"[Title/Abstract] OR "latissimus dorsi"[Title/Abstract] OR "rectus femoris"[Title/Abstract] OR "vastus medialis"[Title/Abstract] OR "vastus lateralis"[Title/Abstract] OR "biceps femori"[Title/Abstract] OR "gluteus medius"[Title/Abstract] OR "soleus"[Title/Abstract] OR "rectus abdominis"[Title/Abstract] OR "internal oblique"[Title/Abstract] OR "external oblique"[Title/Abstract] OR "erector spinae"[Title/Abstract]) AND "muscle activation"[Title/Abstract]

Comentado [AB7]: critical

Comentado [AB8]: Batista et al. [12]

Comentado [AB9]: •The PRISMA guidelines are followed

•The use of multiple databases and a comprehensive search strategy enhances the robustness of the review.

Comentado [AB10R9]: The selection criteria could be elaborated further, particularly regarding how the inclusion of all populations affects the generalizability of the results.

Comentado [AB11]: Check the location of each item. This document only has 19 pages, and the table shows up to 28 pages

Comentado [AB12R11]: item 27: Report the availability of data and materials.

No mention of the availability of supplementary data or materials

Comentado [AB13R11]: Review Protocol (Items 24b and 24c)

Include information on where the review protocol can be accessed and whether there have been any changes.

Comentado [AB14]: Number 13?

Comentado [AB15]: rephrase

AND "electromyography"[Title/Abstract]

2.2 Selection criteria

Studies were eligible for inclusion according to the following criteria:(a) Randomized crossover trials (RCD) published publicly; (b) Subjects include all populations; (c) The experimental group performs training on unstable surfaces (unstable training, UT), while the control group performs training on stable surfaces (stable training, ST); (d) Studies that can provide clear sample sizes, means, and standard deviations; (e) Outcome indicators that met at least one related to electromyography of muscles.

2.3 Data Extraction

From the included studies, import the retrieved literature into Endnote X9 software to remove duplicates, and then BZH and WS will carefully read to decide whether to include it. If there is a disagreement, LZY will be consulted.

The extracted data includes: author, publication time, gender, sample size, age, training experience; author, practice method, practice intensity, Exercise Equipment, muscle activation (stabilizing surface effect, unstable surface effect, no effect difference), outcome indicators [rectus abdominis (RA), internal oblique (IO), external oblique (EO), erector spinae (ES), biceps brachii (BB), trapezius muscle (TM), deltoid muscle (DM), serratus anterior (SA), triceps brachii (TB), pectoralis major (PM), latissimus dorsi (LD), soleus muscle (SM), gluteus medius (GM), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL) and biceps femoris (BF)].

2.4 Assessment of Methodological Quality and Statistical Analyses

Quality evaluation of included literature was conducted using the Cochrane Risk of Bias Assessment Tool recommended by the Cochrane Handbook, classified as low risk, high risk, or unclear risk, and assessed for risk of bias in six aspects: selection bias, performance bias, measurement bias, follow-up bias, reporting bias, and other biases. Statistical analysis of the included data was performed using Stata 16.0 software, quality evaluation of the included literature was conducted through RevMan 5.3 software, and R was used for image processing. I^2 as a statistical measure to evaluate the heterogeneity among studies. When $I^2 < 25\%$, it indicates low heterogeneity; when $25\% \leq I^2 \leq 50\%$, it indicates moderate heterogeneity; and when $I^2 > 50\%$, it indicates high heterogeneity. Subgroup analysis and sensitivity analysis were employed when the combined results exhibited moderate or high heterogeneity. The Egger method, Begg method, and funnel plot method were used to test for publication bias among the studies.

Comentado [AB16]: Citation?

3. Results

Comentado [AB17]: •The meta-analysis is well-structured, with clear presentation of statistical findings.
•Subgroup analyses add depth to the interpretation of the results.

Comentado [AB18R17]: Consider adding a more detailed discussion of heterogeneity sources

3.1 Search Results

A total of 1,971 relevant literature articles were retrieved in this study. Duplicate checking was performed using Endnote, and after removing duplicate articles, 1,681 remained. Based on inclusion and exclusion criteria, articles that clearly did not meet the standards were screened out by reading the titles and abstracts, resulting in 188 articles. After carefully reading the full texts, articles with inconsistent outcome indicators, missing data, or inconsistent reporting were excluded, ultimately yielding 28 articles [13]-[40] (**Figure 1**).[13][40]

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3.2 Study Characteristics

A total of 28 articles[13]-[40] were included in the study, all of which were randomized crossover trials. The total sample size of the included literature was 579 individuals, with the smallest sample size being 8 [37] and the largest being 43 [27]. The average age ranged from 20 to 30 years, with no major diseases. All 28 studies indicated the gender of the participants, with 17 studies focusing on male participants [15],[17],[18][22][23][26][27][29][30][31][32][34][37][38][39][40], 10 studies including both male and female participants [13][14][16][19][20][21][25][28][33][35], and one study focusing on female participants [24]. Ten studies reported on training experience [13, 15, 17, 22-23, 28, 31-32, 38-39].

A total of 52 studies compared the differences in muscle activation between unstable and stable surfaces; in terms of exercise methods, 17 selected push-ups, 6 selected squats, 1 selected weighted half-squat, 7 selected bench press, 3 selected shoulder press, 1 selected muscle-up, 7 selected lunges, 3 selected bridge, 1 selected plank, 1 selected back extension, 2 selected Pilates, 1 selected isometric single-leg stand, 1 selected single-leg deadlift, and 1 selected sit-up. There were 31 studies with body weight as the exercise intensity; there were 21 studies with equipment load as the exercise intensity; in the dependent variables (intermediary media), 6 selected Swiss balls, 1 selected stable surface, 1 selected balance cone, 9 selected Bosu balls, 3 selected Bosu balls and Swiss balls, 1 selected balance board and stability ball, 11 selected TRX suspension, 2 selected mats, 4 selected resistance bands, 2 selected Pilates equipment, 4 selected water tanks, 2 selected stepright, 1 selected Core coaster, 1 selected electric plate, 3 selected wobble boards, and 1 selected stability ball and stable surface for comparison; all 52 studies had multiple control groups, including the impact of different intermediary media on muscle activation. Nine studies indicated that muscle activation was effective on stable surfaces; 43 studies indicated that muscle activation was effective on unstable surfaces; 37 studies indicated no difference in muscle activation between stable and unstable surfaces **(Table 1).**[1340][37][27][15][17][18][22][23][26][27][29][32][34][36][40][13][14][16][19][21][25][28][33][35][24][13][15][17][22][23][28][31][32][38][39]

Comentado [AB20]: There appears to be an inconsistency in the reported number of studies analyzed. The manuscript states that the analysis included 28 studies; however, the results section describes data from a total of 52 studies when categorizing exercise methods, exercise intensity, and dependent variables. This suggests that instead of identifying the correct intersection of studies, the authors may have inadvertently summed different methodological subcategories, leading to an inflated count.

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Comentado [AB22]: idem

Comentado [AB23]: idem

3.3 Evaluation of the quality of the literature

The Cochrane Risk of Bias assessment tool was used to evaluate the methodology of the included literature. Among the 28 studies included in the analysis, 22 used outcome assessment blinding; 20 had complete outcome data; 11 were at low risk of bias, 10 at moderate risk of bias, and 7 at high risk of bias **(Figure 2)**

3.4 Results of Meta-Analysis

The article conducted a meta-analysis on 28 included studies. The unstable surface was used as the experimental group, and the stable surface as the control group. The outcome indicators were divided into core muscles (rectus abdominis, internal oblique muscle, external oblique muscle, erector spinae), upper limb muscles (biceps brachii, trapezius, deltoid, serratus anterior, triceps brachii, pectoralis major, latissimus dorsi), and lower limb muscles (soleus, gluteus medius, rectus femoris, vastus medialis, vastus lateralis, biceps femoris).

3.4.1 Core

Rectus abdominis: The meta-analysis included 14 studies, with 9 studies (21 effect sizes, 396 participants) comparing the effects of UT (experimental group) and ST (control group) on the rectus abdominis. Low heterogeneity (P=0.14, I2=26%) was observed, and a fixed-effect model was used. The meta-analysis results showed a significant difference between the two groups (SMD=0.32, 95%CI: 0.18-0.46, P＜0.01) **(Figure 3)**. Sensitivity analysis showed that the combined results were stable.

Subgroup analysis results **(Table 2)** showed that UT had a better effect when the medium was a Bosu ball (SMD=0.86 vs. 0.78); both exercise intensity and exercise method showed significant trends, with Body-Weight (SMD=0.67) and sit-ups (SMD=1.34 vs. 1.08) showing a more favorable trend.

Internal oblique muscle: A meta-analysis included 14 studies, of which 6 studies (14 effect sizes, 266 participants) compared the effects of UT (experimental group) and ST (control group) on the rectus abdominis. Low heterogeneity was observed (P=0.03, I2=5%), and a fixed-effect model was used. The meta-analysis results showed a significant difference between the two groups (SMD=0.38, 95%CI: 0.20-0.56, P<0.01) **(Figure 4)**. Sensitivity analysis showed that the combined results were stable.

Comentado [AB24]: Internal oblique

Subgroup analysis results showed **(Table 3)** that UT had a better effect when the medium was a Swiss ball (SMD=1.63 vs. 0.89); both exercise intensity and exercise method showed significant trends, with relative load (SMD=1.39 vs. 0.52) and bench press (SMD=1.78 vs. 0.74) showing a more favorable trend.

External oblique muscle: A meta-analysis included 14 studies, of which 6 studies (15 effect sizes, 249 participants) compared the effects of UT (experimental group) and ST (control group) on the rectus abdominis. Moderate heterogeneity was observed (P=0.26, I2=17%), and a fixed-effect model was used. The meta-analysis results showed a significant difference between the two groups (SMD=0.38, 95%CI: 0.20-0.56, P<0.01) **(Figure 5)**. Sensitivity analysis showed that the combined results were stable.

Comentado [AB25]: External oblique

Subgroup analysis results showed **(Table 4)** that UT had a better effect when the medium was a Swiss ball (SMD=2.09 vs. 0.65); both exercise intensity and exercise method showed significant trends, with Body-Weight (SMD=0.72) and sit-ups (SMD=1.12 vs. 0.67) showing a more favorable trend.

Erector Spinae: A meta-analysis included 14 studies, with 9 studies (18 effect sizes, 395 participants) comparing the effects of UT (experimental group) and ST (control group) on the rectus abdominis. There was high heterogeneity (P<0.01, I2=87%), and a random-effects model was used. The meta-analysis results showed significant differences between the two groups (SMD=0.60, 95%CI: 0.17-1.02, P<0.01) **(Figure 6)**. Sensitivity analysis showed stable combined results.

Comentado [AB26]: Erector Spinae

Subgroup analysis results showed **(Table 5)** that UT had better effects when the medium was the TRX suspension (SMD=0.94); both exercise intensity and exercise mode showed significant trends, with Body-Weight (SMD=0.94) and Bridge (SMD=1.23 vs. 0.60) showing a more favorable trend. However, unexpectedly, the use of the Swiss ball (SMD=-0.41, P<0.01), 60%1RM (SMD=-0.36, P<0.01), and Push-Up (SMD=-0.36, P<0.01) in the medium, exercise intensity, and exercise mode, respectively, had negative effects.

Comentado [AB27]: Relative load

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3.4.2 Upper Limbs

Biceps Brachii: A meta-analysis of 4 studies (7 effects, 101 subjects) found that unstable training significantly increased biceps brachii activation compared to stable training (SMD=0.52, 95%CI: 0.23—0.80, P＜0.01), with low heterogeneity among studies (I^2=26%) **(Figure 7)**. Sensitivity analysis showed stable combined results.

Comentado [AB29]: "when 25% ⩽ I^2 ⩽ 50%, it indicates moderate heterogeneity"

Subgroup analysis results **(Table 6)** showed that among the mediating agents, 'TRX Suspension' and 'Elastic Band & Kettlebell' may be significant moderators (P＜0.01); among exercise intensities, '＞50% 1RM' and 'Body-Weight' are significant moderators (P＜0.01); among exercise methods, 'Bench Press' and 'Muscle-Up' may be significant moderators (P＜0.01); among exercise experience, '＞1 year' has a significant activation effect (P＜0.01).

Trapezius: A meta-analysis of 8 studies (26 effects, 540 subjects) found that unstable training significantly increased trapezius activation compared to stable training (SMD=0.23, 95%CI: 0.12—0.35, P＜0.01), with no heterogeneity among studies (I^2=0%) **(Figure 8)**. Sensitivity analysis showed stable combined results.

Subgroup analysis results **(Table 7)** showed that among the mediating agents, 'Bosu Ball' and 'Wobble Board' may be significant moderators (P＜0.01); among exercise intensities, 'Body-Weight' may be a significant moderator (P＜0.01); among exercise methods, 'Push-Up' may be a significant moderator (P＜0.01); among exercise experience, 'none' may be a significant moderator (P＜0.01); among contraction modes, 'concentric contraction' had a better activation effect (P=0.05).

Deltoid: A total of 7 studies (17 effects, 327 subjects) were included. Meta-analysis found that unstable training compared to stable training did not significantly improve deltoid activation (SMD = -0.06, 95% CI: -0.21—0.09, P = 0.44), and there was no heterogeneity among studies (I^2 = 0%) **(Figure 9)**. Sensitivity analysis showed that the combined results were stable.

Subgroup analysis results showed **(Table 8)** that no significant effects were observed for mediators (P = 0.41, I^2 = 0%), exercise intensity (P = 0.44, I^2 = 0%), exercise mode (P = 0.44, I^2 = 0%), training experience (P = 0.44, I^2 = 0%), and contraction mode (P = 0.54, I^2 = 0%) on deltoid muscle activation (P > 0.05). However, in the exercise mode, 'push-ups' were unfavorable for deltoid muscle activation (P = 0.03, 95% CI = -0.94—-0.04, I^2 = 34%); although the Bosu ball showed a negative effect (95% CI: -1.42—-0.13, P < 0.05), since only one study was included, the reliability was low, and thus it was not included for reference.

Serratus anterior: A total of 4 studies (9 effects, 120 subjects) were included. Meta-analysis found no heterogeneity among studies (I^2 = 0%), and a fixed-effect model was used for analysis. Further analysis found that unstable training could significantly enhance serratus anterior activation (SMD = 0.33, 95% CI: 0.07—0.59, P = 0.01), and there was no heterogeneity among studies (I^2 = 0%) **(Figure 10).** Sensitivity analysis showed that the combined results were stable.

Subgroup analysis results **(Table 9)** showed that no significant activation effects were observed on the serratus anterior muscle activation with respect to intermediary, exercise intensity, exercise mode, exercise experience, or contraction mode (P＞0.05). However, UT showed a negative effect in studies where the intermediary was a Swiss ball (95%CI: －0.82—－0.09, P＜0.05).

Triceps brachii: Six studies (12 effects, 191 participants) were included. Meta-analysis revealed no heterogeneity among studies (I^2=0%), and a fixed-effect model was used for analysis. Further analysis found that unstable training significantly increased triceps brachii activation (SMD=0.24, 95%CI: 0.04—0.45, P=0.02) **(Figure 11)**. Sensitivity analysis showed that the combined results were stable.

Subgroup analysis results show **(Table 10)** that in the mediating medium, the 'Swiss Ball' (P＜0.01, 95%CI: －1.45—－0.32, I^2=70%), in exercise intensity, '60%1RM&75%1RM' (P＜0.01, 95%CI: －1.12— －0.28, I^2=58%), and in exercise experience, '＞ 1 year' (P=0.02, 95%CI: －0.40—－0.04, I^2=68%) significantly reduced triceps brachii muscle activation. Meanwhile, in exercise intensity, 'Body-Weight' (P=0.04, 95%CI: 0.01—0.61, I^2=0%) had a significant effect. The article did not observe a significant impact of exercise method (P=0.44, I^2=64%) on triceps brachii muscle activation (P＞0.05). However, in the contraction mode (SMD=0.26, 95%CI: 0.02—0.51, I^2=0%), there was a significant effect (P＞0.05).

Comentado [AB30]: Check table 10

The pectoralis major: Currently, the included original trials (18 effects, 302 participants) consistently found that unstable training compared to stable training had no significant effect on pectoralis major activation **(Figure 12).**

The latissimus dorsi: Currently, the included original trials (10 effects, 154 participants) consistently found that unstable training compared to stable training had no significant effect on latissimus dorsi activation **(Figure 13).**

3.4.3 Lower Limbs

Soleus: Four studies (11 effects, 330 participants) were included. Meta-analysis found that unstable training significantly increased the activation of the soleus compared to stable training (SMD=0.65, 95%CI: 0.42—0.87, $P<0.01$), with moderate heterogeneity between studies (I^2=48%) **(Figure 14)**. Sensitivity analysis showed that the combined results were stable.

Subgroup analysis results **(Table 11)** showed that UT had a statistically significant effect in the squat exercise mode (SMD=0.38).

Gluteus Medius: Two primary studies (5 effects, 284 participants) were included. Meta-analysis found that unstable training significantly increased the activation of the gluteus medius compared to stable training (SMD=0.28, 95%CI: 0.05—0.52, P=0.02), with no heterogeneity between studies (I^2=0%) **(Figure 15)**. Sensitivity analysis showed that the combined results were stable.

Subgroup analysis results **(Table 12)** showed that in terms of exercise mode and intensity, 'lunges' (SMD=0.21, 95%CI: -0.22—0.65, P=0.33) and '10kg' (SMD=0.19, 95%CI: -0.08—0.45, P=0.16) were not significant moderating factors, and they did not significantly increase the activation of the gluteus medius.

Rectus Femoris: Four studies (10 effects, 370 participants) consistently found that unstable training compared to stable training had no significant effect on the activation of the latissimus dorsi **(Figure 16).**

Subgroup analysis results show **(Table 13)** that in terms of exercise method and medium, both 'squat' (SMD=-0.34, 95%CI: -0.66—-0.01, P=0.04) and 'Bosu ball' (SMD=-0.49, 95%CI: -0.87—-0.11, P=0.01) had significant moderating factors, but had a negative activation effect on the rectus femoris.

Vastus lateralis: Three studies (9 effects, 370 participants) consistently found that unstable training had no significant effect on the activation of the latissimus dorsi compared to stable training **(Figure 17).**

Vastus medialis: Four studies (13 effects, 530 participants) consistently found that unstable training had no significant effect on the activation of the latissimus dorsi compared to stable training **(Figure 18).**

Biceps femoris: Four studies (12 effects, 400 participants) consistently found that unstable training had no significant effect on the activation of the latissimus dorsi compared to stable training **(Figure 19).**

3.5 Publication bias analysis results

Among the included studies, the effect on core muscle activation was the most significant, so it was used as an example for funnel plot analysis **(Figure 20)**. The funnel plot showed that the distribution of literature was roughly symmetrical, indicating no publication bias or other biases.

4 Discussion

A total of 28 studies (579 participants) were included to investigate the effects of unstable training on muscle activation, with stable training used for comparative analysis. The meta-analysis results indicate that compared to training on stable surfaces, unstable training significantly enhances muscle activation in core muscles (rectus abdominis, internal oblique, external oblique, and erector spinae),

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Comentado [AB33]: Rectus Femoris

Comentado [AB34]: Vastus lateralis

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Comentado [AB36]: Biceps femoris

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Comentado [AB38]: •The discussion appropriately contextualizes the findings within the existing literature. •The study's limitations are acknowledged

Comentado [AB39R38]: More emphasis on potential confounding factors (Experience and Skill Level, Fatigue , Limb Dominance...etc) influencing muscle activation in unstable training would strengthen the discussion.

upper limb muscles (biceps brachii, trapezius, serratus anterior, and triceps brachii), and lower limb muscles (soleus and gluteus medius). Subgroup analysis shows that participant characteristics (with or without training experience) and muscle activation protocols (exercise type, intensity, medium, and contraction mode) potentially moderate the combined effects of unstable training on various muscle indicators. The results of each outcome indicator will be discussed and analyzed in depth below.

4.1 Core

The core muscles play a bridging role in the transfer of strength between the upper and lower extremities [41]. Compared to stable environments, unstable environments require continuous balance adjustments, and the core muscles must participate more actively [6],[42]. The aggregated results show that unstable training can significantly increase the activation of core muscles ($P < 0.01$). The overall findings support the previous meta-analysis by Batista GA et al. [12], which found that unstable training significantly enhances the activation of core muscles (rectus abdominis, external oblique, internal oblique, erector spinae, and lumbar multifidus). However, Batista GA et al. [12] included experiments with large variations in study design, participant characteristics (such as age, gender, training level), and training variables (such as frequency, duration, intensity), which may lead to high overall heterogeneity in the included studies. Additionally, key factors such as training intensity, training duration, participants' physical fitness, and training experience were not strictly screened and grouped, making it difficult to clearly distinguish the effects of different unstable exercises, which may affect the comprehensive understanding of core activation. Furthermore, fewer studies were included in the research on the internal oblique and lumbar multifidus (2 and 4 studies, respectively), which may affect the statistical significance and accuracy of effect size estimation, making the results more susceptible to random factors, leading to instability and a higher risk of bias. Sensitivity and detailed subgroup analyses were not conducted. In contrast, the article included at least 6 studies on core muscles, providing a detailed analysis of different unstable equipment, training intensity, and exercise methods, with higher quality of included literature.[41][6][42][12][12]

Meanwhile, the subgroup analysis of the article further indicates that, compared to stable training, intermediary, practice intensity, and practice method are significant moderating factors affecting core muscle activation. Among them, using the Bosu ball, body weight, and sit-ups are the best schemes for activating the RA. This is consistent with the results of the systematic review by Oliva-Lozano JM et al. [43], which indicated that upper-body unstable sit-ups on the Bosu ball achieved the highest RA activation effect, and bodyweight training had a significant effect on rectus abdominis activation, especially during core stability exercises without load. Using the Swiss ball, relative load, and bench press are the best schemes for activating the IO. This may be because the IO is located deep within the external oblique [44], and the bench press, as a compound strength training movement, involves the collaboration of multiple joints and muscle groups. When the bench press is performed in an unstable environment, the increase in weight enhances neural activation [45], and to maintain body balance, the internal oblique muscle is more involved in spinal stability [46]. Bezerra et al. [47] also found that using the Swiss ball for upper-body instability yielded more significant effects than lower-body instability. Using the Swiss ball, body weight, and sit-ups are the best schemes for activating the EO. This may be related to the external oblique's primary role in trunk rotation, lateral flexion, and assisting in maintaining trunk stability [48], and all the included studies involved upper-body instability. Using the TRX suspension, body weight, and bridge are the best schemes for activating the ES. This finding is also consistent with previous research by Lee D et al. [49]. Since the muscle activity of the ES during the bridge at a high suspension position was significantly higher than at a low suspension position ($P < 0.05$).

Additionally, studies by Yoon JO et al. [50] and Bi Xia et al. [51] also confirmed significant effects of the erector spinae during unstable bridges. Furthermore, Oliva-LozanoJM et al.'s [43] systematic review also indicates that the maximum activity in RA, EO, and ES is found on body weight. However, unexpectedly, the use of the Swiss ball, 60% 1RM, and push-ups resulted in a significant reduction in ES activation. Specifically, the primary task of the erector spinae is to maintain an upright posture along the spine [52], and compared to push-ups performed on a stable surface, push-ups on a Swiss ball rely more on shoulder, chest, and core stability, while the significant reduction in force production may be due to the muscles around the shoulder complex prioritizing stability over force generation [53], which leads to more trunk control required on unstable surfaces, with the activation of the abdominal and lateral abdominal muscles often exceeding that of the erector spinae, which is relatively inhibited in this process. However, in some cases, unstable conditions produce better effects than stable conditions. These better effects are produced in the last execution of the exercise with a higher number of repetitions (22-25 times) [54].[43][44][45][46][47][48][49][50][51][43][52][53][53]

In summary, unstable training can effectively activate the abdominal core muscles. Targeted core stability training is best performed simultaneously with core activation to have marginal benefits for sports performance [55].[55]

4.1 2 Upper Limbs

Properly activating the upper limb muscles not only enhances strength output but also improves neuromuscular coordination and reduces the risk of injury [56]. Particularly during high-intensity training, pre-training upper limb activation helps achieve better muscle coordination in subsequent training, improves training effectiveness, and reduces technical errors caused by fatigue [57]. The article finds that unstable training can increase the activation levels of the biceps brachii, trapezius, serratus anterior, and triceps brachii. Subgroup analysis results indicate that individuals with more than 1 year of exercise experience achieve the best activation effects by performing the muscle-up exercise using a TRX suspension combined with body weight during BB training. This may be because exercising on a TRX suspension requires greater synergistic effort from the upper limbs and core muscles, and suspension exercises can achieve training effects close to traditional 70% 1RM intensity, making them more suitable for advanced training by highly skilled individuals [58]. Meanwhile, Aguilera-Castells.In the systematic review by J et al. [59], it was noted that varying the grip on the TRX suspension led to significant differences in biceps brachii activation due to changes in trunk-leg inclination and hip flexion angles. Using an overhand or neutral grip can increase biceps brachii activation levels [58]. For individuals with limited training experience, the most effective method for TM activation is the push-up on a Bosu ball combined with body weight, with more pronounced effects during the concentric phase. This may be because the Bosu ball provides greater instability [60], requiring higher control of the scapula on an unstable surface [61] to prevent scapular displacement under unstable conditions [62]. From a physiological perspective, under unstable conditions, concentric contractions require higher muscle activation to counteract the dual influence of gravity and instability. This contraction increases the recruitment of muscle fibers, particularly in the upward and medial scapular movements, where the upper and middle trapezius are more highly activated to maintain shoulder stability [63]. Additionally, concentric contractions under unstable conditions require rapid responses to counteract minor displacements caused by instability. These rapid responses help increase the number of muscle units recruited and enhance the muscle's instantaneous control ability [64]. SA should avoid using the Swiss ball during exercises to reduce the activation of the serratus anterior. Cools et al. [65] found that push-ups on a Swiss ball may result in insufficient upward rotation of the scapula or excessive

Comentado [AB40]: Rephrase

involvement of the upper trapezius, leading to decreased activation of the serratus anterior. This is related to the higher center of gravity and greater instability of the Swiss ball [66]. Although this benefits the activation of core muscles, the high instability of the ball may cause the body to prioritize the activation of other muscle groups to maintain stability, resulting in relatively reduced activation of the serratus anterior [67]. Finally, for TB training, bodyweight training yields the most significant activation effects, while individuals with more than one year of training experience achieve greater activation on a Swiss ball with intensities exceeding 60% of 1RM.Training with Swiss balls may lead to negative effects. This could be because combined strength training centered around Swiss balls can improve body stability, reduce the degree of shift in body center of gravity [68], resulting in more attention and energy being diverted to the involvement of core and stabilizing muscles, forcing the core muscles to collaborate more to maintain balance, thereby reducing the activation of the triceps brachii [61]. Behm et al. [1] found that under unstable conditions, due to increased joint stiffness during movement execution, coordination, force, and performance may be hindered. Movements may become harder to control, leading to insufficient activation of the target muscles [69]. Experienced exercisers are better at recruiting target muscles on stable surfaces. Koshida et al. [70] discovered that under unstable conditions, experienced individuals tend to engage more synergistic muscles to maintain balance, thereby reducing direct involvement of the target muscles, while beginners may rely more on the target muscles for movement execution due to their lower coordination and synergistic muscle involvement. However, bodyweight exercises significantly enhance training intensity. In resistance training, the triceps brachii primarily functions in elbow extension [71]. Compared to training in stable environments, unstable training primarily provides additional engagement to maintain elbow stability during triceps activation [72]. Additionally, when the glenohumeral joint is in an unstable environment, triceps activation increases [73]. During bodyweight training, the load is relatively light, increasing reliance on smaller muscles like the triceps, which are more activated to assist in controlling instability [74].[56][57][58][59][58][60][61][62][63][64][65][66][67][68][61][1][69][70][71][72][73][74]

In conclusion, unstable training can promote greater neuromuscular adaptations, such as reduced co-contraction, improved coordination, and increased confidence in performing skills [1]. Trainers should develop a feasible training plan based on their own training experience, level, and goals, and implement it during the training process.[1]

4.1 3 Lower Limbs

Activation of lower limb muscles is not only controlled by local motor functions but also neuro-coupled with upper limb movements, influencing overall motor coordination. During maximal effort movements, activating lower limb muscles can regulate whole-body force output and improve athletic performance [75]. The study found that unstable training significantly activates the soleus and gluteus medius muscles, and subgroup analysis results indicate that squats have a significant effect on soleus muscle activation. The soleus muscle is located on the posterior side of the calf, deep to the gastrocnemius muscle [76]. The soleus muscle is one of the key muscles in the lower limb for maintaining posture and balance, playing a critical role in posture control [77]. Under unstable conditions, the body requires more complex neuromuscular coordination to maintain balance, which improves neuromuscular coordination, increases the H-reflex amplitude of the soleus muscle, and may indicate disinhibition of the neuromuscular pathway and higher adaptability [78]. Deep muscles are additionally activated to meet posture control demands in optimizing athletic performance [79]. Unstable environments significantly increase the demand for posture control, enhancing the soleus muscle's ability to respond to postural disturbances, allowing it to activate more quickly during dynamic tasks to maintain ankle stability and body balance [22]. Behm et al. [1] also indicated that during squats, the soleus muscle may bear more postural responsibility than the quadriceps, making it logical to expect greater soleus muscle activity under unstable conditions. Additionally, it is noteworthy that in soleus muscle activation, bench press and push-ups could not be further analyzed due to insufficient study numbers, but based on current analysis, they still show significance [13][28]. In gastrocnemius muscle activation, although unstable training has an activating effect on the GM (P=0.02), it did not show statistical significance in subgroup analysis. Krause et al. [80] have fully demonstrated that the gluteus medius exhibits a greater muscle activation trend on surface instability. Youdas JW et al.Research from 2015[81] indicates that unstable surface training provides a stronger stimulus for gluteus medius activation compared to stable surfaces, a result of increased load on the hip abductors. The abductor load forces the body to stabilize the pelvis and maintain balance by activating the gluteus medius, which must bear more load to prevent excessive pelvic tilt and maintain hip stability, significantly increasing its demand for stabilization function[80]. Additionally, the hip abductor load enhances the nervous system's recruitment frequency and intensity of the gluteus medius to coordinate hip and pelvic stability, resulting in a significant increase in its electromyographic activity, showing higher muscle activation levels compared to stable surfaces[82]. Compared to movements primarily involving hip activities, the lunge action mainly involves hip flexion and knee coordination, with limited activation demand for the gluteus medius as the primary hip abductor muscle[83]. However, it remains unclear whether and how hip stabilizing muscles adjust their activation patterns from stable to unstable support conditions during weighted leg extension tasks[84]. The RF, being the most superficial muscle of the quadriceps, exhibits different oxygen delivery strategies and motor responses compared to deeper muscles during movement[85]. In unstable training, there is often a greater emphasis on the coordinated work of core and postural muscles rather than isolated activation of the rectus femoris[86], which may result in less significant activation effects. Furthermore, due to its cross-joint function and superficial anatomical position, the rectus femoris may respond less significantly to unstable loads compared to deeper muscles[87]. Subgroup analysis results show that the Bosu ball has a negative effect on rectus femoris activation, possibly because using a Bosu ball during squats limits the trainee's ability to use heavier weights for load training, affecting strength gain[88][89]. During exercise, activation of the rectus femoris may be more allocated to synergistic muscles to maintain overall stability, thereby reducing its training load[90]. Under unstable conditions, while the rectus femoris is activated, there is a certain degree of reduction in lower limb force output, weakening overall dynamic stability of the lower limb, and the effects achieved are less significant compared to training under stable load conditions. The article is the first to discover a negative activation effect of using a Bosu ball during squats for individuals with extensive exercise experience. Future research requires more original trials to validate the article's preliminary findings.[75][76][77][78][79][22][1][13][28][80][81][80][82][83][84][85][86][87][88][89][90]

Comentado [AB41]: [13,28]

Comentado [AB42]: al. research

Comentado [AB43]: 88,89

4.2 Physiological Mechanisms of Unstable Training in Promoting Muscle Activation

Unstable training is a widely used method to enhance physical fitness and improve neuromuscular control. Its core concept lies in promoting the body's neuromuscular system to adapt accordingly by exercising in unstable environments, thereby increasing muscle activation levels [91]. In this process, multiple studies have shown [92],[93],[94] that load is the main variable stimulating superficial muscle activity, requiring the nervous system to increase the recruitment of motor units [95],[96], especially higher threshold motor units [97], to maintain body stability. At the same time, when performing training that changes muscle work conditions, it is not only necessary to consider changes in muscle strength activity but also pay attention to changes in exertion patterns [98]. Among them, the role of the kinetic chain effect, motor muscles, and stabilizing muscles in unstable training should be clearly understood. The kinetic chain is the process by which the body transmits force from the core region to distal joints and muscles through the myofascial connection system to complete coordinated movements [99]. This effect is particularly important in unstable environments, helping to enhance stability and the precision of movements. Stabilizing muscles, through contraction, promote joint stiffness and respond to disturbances early through feedforward or feedback control mechanisms [100]. Unstable training primarily focuses on neural adaptability of muscles, and UT seems to provide better adaptive stimuli for stabilizing muscles than for primary motor muscles [84]. Additionally, unstable movements seem more suitable for weight loss programs, as total energy expenditure is significantly greater when exercising on unstable platforms.[91][92][94][95][96][97][98][99][100][84]

In terms of muscle fiber types, under normal circumstances, the body's low-threshold type I muscle fibers are preferentially recruited over high-threshold type II muscle fibers, especially in light and low-intensity exercise tasks [101]. However, under unstable conditions, the recruitment order of muscle fibers not only follows the size principle (such as preferentially recruiting type I slow fibers) but may also recruit some type II fast fibers due to increased instability, to quickly respond to balance challenges and posture adjustments [102]. Therefore, in unstable training, the upper limb muscles exhibit higher levels of type II muscle fiber recruitment in unstable environments [103], enabling trainees to better cope with external changes.[101][102][103]

In terms of proprioception. When the external environment changes, the proprioceptors in the joints, tendons, and muscles (such as muscle spindles and Golgi tendon organs) become more sensitive to help the body perceive position and adjust posture [104]. The feedback from the receptors is processed by the central nervous system, further enhancing muscle activation efficiency and neuromuscular coordination. This helps promote motor learning and neuroplasticity [105], directly reflected in the improvement of one's ability to control muscles.[104][105]

4.3 Limitations of the study

Although this meta-analysis included literature that underwent strict selection and exclusion, there are still certain limitations. First, among the 28 included papers, it was not possible to fully analyze all existing intermediary media, exercise intensity, and exercise methods, and the coverage of exercise experience and contraction patterns was not complete, with some lacking corresponding cross-analysis. Second, some of the included articles had small sample sizes. Third, in the included literature, there was a lack of separate unified female participants, leading to an inability to analyze differences between men and women in unstable training. Finally, due to the heterogeneity of the trials and individual differences among participants, this could lead to some data having heterogeneity, potentially causing bias in the results.

4.4 Practical Applications

The article systematically reviewed the effects of unstable training on the activation of different upper limb muscles. Through subgroup and sensitivity analyses, while ensuring the quality of the literature, it explored the effects of unstable training on intermediary media, exercise intensity, exercise methods, training experience, and contraction patterns, as well as potential regulatory effects, thereby enhancing the credibility and scientific nature of the research results.

Unstable training significantly improved the activation levels of core muscles (rectus abdominis, internal oblique, external oblique, erector spinae), upper limb muscles (such as biceps brachii, trapezius, serratus anterior, and triceps brachii), and lower limb muscles (soleus and gluteus medius) statistically.

Comentado [AB44]: ??

Comentado [AB45]: consider expanding on how these findings could be implemented in real-world settings (e.g., specific training protocols for athletes or rehabilitation programs)

Comentado [AB46]: Begin the sentence with "Statistically, unstable...

Notably, when training on unstable surfaces, the body needs to coordinate a large number of muscle groups and continuously adjust stability to maintain balance, which may lead to unstable blood pressure increases [106]. For individuals at higher cardiovascular risk (such as those with hypertension or coronary heart disease), the increased demand for neuromuscular control and response during training on unstable surfaces may significantly elevate heart rate and respiratory frequency, placing greater strain on the cardiovascular system and increasing health risks. Additionally, the increased activity of the sympathetic nervous system under unstable training conditions may further lead to elevated blood pressure and accelerated heart rate, increasing the risk of cardiovascular emergencies. For individuals with weak strength, it is advisable to use body weight and take protective measures when choosing unstable training to avoid sports injuries. Finally, for individuals with sports injuries, unstable training mobilizes multiple joints and coordinates the distribution of different motor units, which helps increase muscle activation under lower loads, reduce compensatory movements, and effectively promote functional recovery, enhance core stability, improve neuromuscular control, enhance balance and coordination, and prevent secondary injuries. Therefore, future research should focus on the needs of different populations to determine more accurate selection schemes, integrate them with specialization, and explore the multidimensional value of unstable training.[106]

5. Conclusion

Comentado [AB47]: The conclusion could better highlight future research directions, particularly regarding the unresolved questions from the subgroup analyses. Consider restating key limitations and how they might impact the interpretation of the findings.

Unstable training can enhance the activation levels of core muscles (rectus abdominis, internal oblique, external oblique, erector spinae), upper limb muscles (biceps brachii, trapezius, serratus anterior, triceps brachii), and lower limb muscles (soleus, gluteus medius). Therefore, unstable training can be considered as a more effective form of non-stable surface activation.

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Author contributions

BZH designed the study and search strategy. BZH and WS performed abstract and full-text screening, methodological quality, and bias analysis, and contributed to the completion of screening and data extraction for all data within this manuscript. BZH and WS designed and calculated meta-analyses, subgroup analyses, sensitivity analyses, and publication bias, and created images and tables.BZH wrote the preparation of the first draft, reviewed and edited it, and finally finished the final draft. WS facilitates the critical evaluation of the findings and the drafting of manuscripts. BZH, LZY, WS participated in editing and revising the final version of the manuscript. All authors read and approved the final version of the manuscript and agreed with the authors' theoretical statements.

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Competing interests

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