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Review

The merit of superimposed vibration for flexibility and passive stiffness: A systematic review with multilevel meta-analysis

Daniel Jochum [a,*], Andreas Konrad [b], Lars H. Lohmann [c], Darryl Cochrane [d], Jörn Rittweger [e,f], Viola Vogel [a], Konstantin Warneke [b]

[a] Department of Health Sciences and Technology, ETH Zurich, Zurich 8006, Switzerland
[b] Institute of Human Movement Science, Sport and Health, University of Graz, Graz 8010, Austria
[c] Department of Human Motion Science and Exercise Physiology, Friedrich Schiller University Jena, Jena 07749, Germany
[d] School of Sport, Exercise and Nutrition, College of Health, Massey University, Palmerston North 4442, New Zealand
[e] Institute of Aerospace Medicine, German Aerospace Center (DLR), Cologne 51147, Germany
[f] Department of Pediatrics and Adolescence Medicine, University Hospital Cologne, Cologne 50937, Germany

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Abstract

Background: Due to its high relevance in sports and rehabilitation, the exploration of interventions to further optimize flexibility becomes paramount. While stretching might be the most common way to enhance range of motion, these increases could be optimized by imposing an additional activation of the muscle, such as mechanical vibratory stimulation. While several original articles provide promising findings, contradictory results on flexibility and underlying mechanisms (e.g., stiffness), reasonable effect size (ES) pooling remains scarce. With this work we systematically reviewed the available literature to explore the possibility of potentiating flexibility, stiffness, and passive torque adaptations by superimposing mechanical vibration stimulation.
Methods: A systematic search of 4 databases (Web of Science, MEDLINE, Scopus, and Cochrane Public Library) was conducted until December 2023 to identify studies comparing mechanical vibratory interventions with passive controls or the same intervention without vibration (sham) on range of motion and passive muscle stiffness in acute (immediate effects after single session) and chronic conditions (multiple sessions over a period of time). ES pooling was conducted using robust variance estimation via R to account for multiple study outcomes. Potential moderators of effects were analyzed using meta regression.
Results: Overall, 65 studies (acute: 1162 participants, chronic: 788 participants) were included. There was moderate certainty of evidence for acute flexibility (ES = 0.71, $p < 0.001$) and stiffness (ES = −0.89, $p = 0.006$) effects of mechanical vibration treatments *vs.* passive controls without meaningful results against the sham condition (flexibility: ES = 0.20, $p < 0.001$; stiffness: ES = −0.19, $p = 0.076$). Similarly, moderate certainty of evidence was found for chronic vibration effects on flexibility (control: ES = 0.64, $p = 0.043$; sham: ES = 0.65, $p < 0.001$). Lack of studies and large outcome heterogeneity prevented ES pooling for underlying mechanisms.
Conclusion: Vibration improved flexibility in acute and chronic interventions compared to the stand-alone intervention, which can possibly be attributed to an accumulated mechanical stimulus through vibration. However, studies on biological mechanisms are needed to explain flexibility and stiffness effects in response to specific vibration modalities and timing.

Keywords: Whole-body vibration; Stretching; Foam rolling; Range of motion; Muscle stiffness

1. Introduction

The American College of Sports Medicine classified flexibility as one of the 5 most important health-related physical capacities.[1] Furthermore, reaching sufficiently high joint range of motion (ROM) is considered a fundamental ability with assumed benefits for physical performance,[2,3] injury risk,[4,5] or joint health[6] in the general population and the elderly. It is thus not surprising that a plethora of flexibility research has been performed to facilitate effective training and treatment programs.[3,6–12] Currently, 2 theories explain increases in joint

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* Corresponding author.
E-mail address: djochum@ethz.ch (D. Jochum).

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ROM. The mechanical theory attributes increased ROM to a decrease in apparent passive joint stiffness at rest (i.e., joint passive torque change per angle change), changes in mechanical properties (i.e., alterations of tissue stiffness), or structural adaptations (e.g., increased fascicle length). In contrast, the sensory theory suggests a reduced sensibility for stretching pain (i.e., increased pain threshold) with negligible structural adaptations (resistive torque) after an intervention.[13,14]

When seeking improved flexibility, stretching can be assumed one of the most common interventions. Simply elongating the muscle fibers by increasing the distance between the muscle origin and attachment creates mechanical tension that is sufficient for acute[4,15] and chronic[8] flexibility enhancements. Although it is proven effective as a stand-alone intervention, the mechanical stress applied to the muscle can be enhanced by adding contractions in the stretched muscle position. One method for inducing this type of stimulation has been explored in cell,[16] animal,[17] and recent human studies[18] by using electromyostimulation during stretching.[18,19] Alternatively, active contractions at extended muscle lengths are also considered to be effective by Alizadeh et al.,[20] whose review emphasized that full ROM resistance training can be considered a form of loaded dynamic stretching. This type of training involves adding contraction to the end ROM, leading to flexibility improvements with an effect size (ES) of 0.73.

Another method to activate a muscle and induce contractions was proposed via vibration training.[21] Vibrations can enhance blood flow and temperature,[22] thereby activating thermo-sensory transient receptor potential ion channels,[23,24] while mechanical stretch and deformations can actuate mechano-gated Piezo Channels.[25,26] These sensory channels produce action potentials in attempt to reduce the vibratory waves, which might otherwise cause tissue damage if excessive.[27] The so-called tonic vibration reflex (TVR)[28] might induce motor unit activation[29,30] via monosynaptic and polysynaptic pathways,[31] thus stimulating the length-detecting Ia-afferent fibers (primary endings of the muscle spindles).[32] The facilitated activation of the α-motoneurons causes reflective tonic contraction of the muscle, which can be superimposed to other interventions, such as stretching.

However, systematic literature reviews on vibration effects are scarce. The latest systematic reviews from 2022[33] and 2019[34] qualitatively investigated whole-body vibration flexibility adaptations, while the only meta-analysis that quantified vibration effects on flexibility was performed in 2013 and included 19 studies in total.[35] Also, more than a decade has passed since Cochrane[36] examined the effects of vibration training on sports performance, especially flexibility, in athletes.

Vibration-induced flexibility improvements were attributed to a series of physiological responses beyond enhancing blood circulation, including enhanced motor unit recruitment[30] and increased muscle activation,[37] while effects on passive muscle−tendon stiffness or passive resistive torque remain unclear.[34] To close this gap in the literature, the goal of this systematic review is to explore the possibility of improving flexibility, stiffness, and torque adaptations by superimposing mechanical vibration. It was hypothesized that mechanical vibration would lead to significant improvements in ROM both acutely (immediately following a single session) and chronically (long-term intervention with multiple sessions over a period of time) compared to a passive control. Additionally, it was expected to be more effective against the same intervention without additional vibratory stimulation (sham conditions).

2. Methods

In accordance with ethical publishing standards,[38] this systematic review with meta-analysis was registered in the International Prospective Register for Systematic Reviews (PROSPERO) under registration-number CRD42023484821. The review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for systematic review with meta-analysis.[39]

2.1. Literature search

The search-term guided literature screening was conducted in 4 online databases (Web of Science, MEDLINE, Scopus, and Cochrane Public Library) in December 2023. Specific search terms based on the requirements of each database were produced, with the exemplary PubMed database search term provided as follows: ((vibration) AND (muscle OR tendon OR tissue) AND (tone OR stiffness OR elasticity OR flexibility OR extensibility OR range of motion))

The remaining search terms can be reviewed in the Supplementary Table 1.

Eligibility criteria were applied under consideration of the PICO (Participants/patients, Intervention, Comparison, Outcome) guidelines:[40,41] original research articles in the English language were included if they used:

(a) Human studies with healthy subjects regardless of age;
(b) Soft tissue vibration treatment (muscle, tendons, ligaments, fasciae);
(c) A comparison to another group with the exact same intervention without vibration (sham) or no intervention (control);
(d) Outcome measurements of soft tissue viscoelastic characteristics (stiffness, tone, elasticity, flexibility, extensibility, ROM, passive torque).

Furthermore, delayed onset muscle soreness studies were excluded due to measurements taken in a fatigued state.

2.2. Methodological study quality and risk of bias

Risk of bias assessment was performed by 2 independent investigators (DJ and LHL) using the Physiotherapy Evidence Database (PEDro) scale.[42,43] In the event of a disagreement, it was resolved by a 3rd examiner (AK) who made the final decision. Additionally, publication bias risk was assessed by visually inspecting the modified funnel plots for multiple study outcomes.[44] Egger’s regression tests were used with an

extension for dependent ES to provide additional quantification.[44] According to the Grading of Recommendations, Assessments, Developments, and Evaluations (GRADE) criteria,[45] the certainty of evidence was initially classified as high and adjusted afterwards based on the risk of bias score, inconsistency, uncertainty of directness, imprecise data, reporting bias (all of which downgrade), strong evidence of association, evidence of a dose−response gradient, and plausible confounders (all of which upgrade the level of evidence). Certainty was categorized as "very low" (effect estimate very uncertain), "low" (further research very likely to change the effect estimate), "moderate" (further research may change the effect estimate), or "high" (further research unlikely to change the effect estimate).

2.3. Treatment characteristics

All included vibration studies were evaluated according to the reporting guidelines for whole-body vibration studies in humans, animals, and cell cultures: a consensus statement from an international group of experts[46] superseding the previous reporting recommendations.[47] According to these guidelines, a total of 26 items should be reported, including details about the device used (2 items), the type of vibration (5 items), the administration of vibration (9 items), the protocol (7 items), and the participants (3 items). When focusing on whole-body vibration studies, not all items apply to other forms of vibration, such as vibration dumbbells.

2.4. Definitions and terms

Vibration is often added to foam rolling and/or stretching. Foam rolling is described as dynamically rolling the body (or segments of it) with prescribed velocity and duration over a foam roll.[9−12,48] Stretching definitions are less intuitive. The concept of static stretching is defined according to Behm[49] as the lengthening of a muscle until a stretch sensation or point of discomfort is reached while holding this position for a prescribed duration. When a (sub)maximal contraction is added, this technique is considered proprioceptive neuromuscular facilitation (PNF) stretching. For dynamic stretching, different authors have provided different approaches and definitions. This analysis has adopted the definition from Warneke and Lohmann,[50] which refers to controlled back-and-forth movements in the end ROM. In contrast, ballistic stretching, as defined, involves less controlled, bouncing movements in the end ROM.[3] This differentiation separates dynamic stretching from full ROM resistance training (full ROM dynamic movements over full ROM[20]). Since this review also included dynamic activities with added vibration stimuli, this type of movement was not associated with the dynamic stretching subgroup.

Apart from intervention definitions, it is important for us to define flexibility and ROM. According to Gleim and McHugh,[51] static flexibility can be defined as "the range of motion. . .available to a joint or series of joints" (p.289) while dynamic flexibility "refers to the ease of movement within an obtainable ROM" (p.290). Therefore, ROM is related to flexibility, but they are not identical. Another outcome to consider is passive peak torque, which is often used interchangeably with onset of stretching pain.[52]

Stiffness is defined as force change per unit length adaptation in linear movement or as torque per unit angle change. This review only utilizes passive stiffness, which refers to the muscle's state at rest without active contraction. Increases in passive stiffness may emerge either from thickened or shortened fascial tissues or from increased residual muscle stiffness, which may limit ROM and be detrimental to flexibility.

The current analysis includes studies of acute and chronic stimulation on ROM, stiffness, and passive torque properties. Acute studies measure effects immediately following an intervention, while chronic studies involve interventions performed over a period of at least 2 weeks with a minimum of 1 session per week.[53]

2.5. Data processing and statistics

Data were extracted by DJ and KW and double-checked by JR and DC. For further processing, collected means (M) and standard deviations (SDs) were inserted into a Microsoft Excel (Version 16.84; Microsoft, Redmond, WA, USA) spreadsheet and mean differences as well as pooled SD were calculated using (as required for the robust variance estimation (RVE) package in R[54] (Version 4.4.2; The R foundation for Statistical Computing, Vienna, Austria) using the following formulas:

$$M(difference) = M(posttest) - M(pretest) \qquad \text{Eq. (1)}$$

SD were pooled as follows:

$$\mathrm{SD}_{\text{pooled}} = \sqrt{\frac{(n_1 - 1) \times \mathrm{SD}_1^2 + (n_2 - 1) \times \mathrm{SD}_2^2}{(n_1 - 1) + (n_2 - 1)}} \qquad \text{Eq. (2)}$$

As suggested by Fisher and Tipton,[54] the RVE meta-analytical calculation model was chosen to account for dependent multiple study outcomes with unknown origin of variance as performed in other recently published meta-analyses.[11,50,55] The ES for the vibration group and comparisons (active-sham or passive control) are given as standardized mean differences (SMD) and 95% confidence intervals (95%CIs). To minimize methods and outcome heterogeneity (τ^2), subgroup analyses were performed for local vibration applications, stretching, body-weight exercises, and foam rolling with and without superimposed vibration on ROM and tissue passive properties. The investigation methods were further differentiated for ROM (active and passive movement), passive stiffness (ultrasound with shear-wave elastography and indentation methods with myotonometry and hardness meter), and passive torque (passive resistive torque at joint neutral position, passive peak torque at maximum ROM, passive torque at first sensation of stretch, passive stiffness as ratio between torque variation and ROM, as well as tendon stiffness measured by tendon elongation). Furthermore, meta-regression was conducted to assess ES correlation (β_0) with vibration training parameters (vibration frequency, amplitude, acceleration, and training duration). Pooled ES were interpreted as follows: trivial: $0 \leq \text{ES} < 0.2$, small: $0.2 \leq \text{ES} < 0.5$,

moderate: $0.5 \leq ES < 0.8$, and large: $ES \geq 0.8$.[56] All calculations were performed using R and the robumeta package,[54] considering study design (parallel and cross-over design). Results were visualized with Excel (Version 16.84, Microsoft).

3. Results

3.1. Qualitative analysis

3.1.1. Search results

The literature search procedure, which resulted in 65 studies[57–121] meeting the inclusion criteria, is illustrated in Fig. 1. A description of each study is given in the narrative table in the supplemental material (Supplementary Table 2).

If eligible studies did not provide original values (mean ± SD), data were requested from the authors or taken from graphics where possible. Accordingly, studies could exclusively be considered for further inclusion if (a) authors sent the requested data,[109] or (b) M and SD could be imputed from graphics.[58,63,64,71,85,89,98,102,108,113,121] In all other cases, studies had to be excluded.

The 65 included studies[57–121] contained 246 ES with data from a total of 1884 participants, comprising males (n = 1000), females (n = 719), and without information regarding sex (n = 165); 4 studies included 165 participants without information regarding sex.[67,82,92,118] Note that 22 studies investigated males[57,59,64,68,75,79,85,86,88–90,93,94,96,100,104,105,107,108,111,113,116] and 14 studies looked at females only.[60,63,69,70,73,76,81,83,87,91,101,102,112,117] The age was 25 ± 11 years, with 2 studies not reporting age.[114,118] Two studies investigated older adults over 60,[81,119] and 4 studies included young subjects around 10 years old.[65,67,91,113] Participant characteristics are presented in Supplementary Table 3.

Out of 46 acute studies[57–59,62–71,75,77,79,80,84,85,88,90–100,102–109,111–114,116,119,121] including 1162 participants (males = 774, females = 333, not reported = 55) with an age of 23.06 ± 8.70 years, 17 compared vibration training with a passive control group,[59,62,69,79,80,88,94,99,100,104–107,111,112,114,116] while 39 sham intervention comparisons were included,[57,58,62–71,75,77,80,84,85,88,90–93,95–98,100,102–106,108,109,111–113,119,121] meaning 10 studies included both conditions.[62,69,80,88,100,104–106,111,112] Concerning sham conditions, 12 studies investigated stretching,[69,85,90–92,100,102,106,111,113,119,121] 11 foam rolling,[62,80,84,88,96–98,104,105,108,112] and 16 body-weight exercises[57,58,63–68,70,71,75,77,93,95,103,109] with and without superimposed vibration. Of all acute studies, 41 addressed ROM,[57–59,62–67,69–71,75,77,79,84,85,88,90–100,102,104–108,111–114,119,121] 11 addressed stiffness,[68,79,80,88,99,103–105,108,114,116] and 5 addressed a form of passive torque.[105,107–109,111] Exercise durations ranged from 10 s to 60 s for stretching, 20 s to 2 min for foam rolling, and 15 s to 6 min for body-weight exercises, with 1–10 repetitions and local vibration applications up to 15 min (Supplementary Table 4).

Chronic training effects were examined in 22 studies[60,61,67,71–74,76,78,81–83,86,87,89,101,110,113,115,117,118,120] including 788 participants (males = 251, females = 405, not reported = 132) with an age of 28 ± 15 years. Ten studies compared vibration to a passive control[60,73,74,76,81,86,87,110,115,118] and 14 to an active sham condition,[61,67,71,72,74,78,82,83,89,101,110,113,117,120] meaning 2 studies included both conditions.[74,110] Concerning sham conditions, 2 studies investigated stretching,[74,113] 2 studies investigated foam rolling,[82,89] and 10 studies investigated body-weight exercises[61,67,71,72,78,83,101,110,117,120] with and without superimposed vibration. Of all chronic studies, 18 studies investigated ROM,[60,67,71–74,76,78,82,83,86,87,89,101,113,117,118,120] 2 studies investigated stiffness,[61,115] and 4 studies investigated a type of passive torque.[78,81,89,110] Long-term (chronic) study intervention periods ranged from 3 to 16 weeks with 1–5 sessions per week and compared stretching for 10 s to 30 s, foam rolling for 60 s, and exercise training for 30 s to 120 s (Supplementary Table 5).

Passive torque measurement methods differentiated passive resistive torque at joint neutral position,[108] passive peak torque at maximum ROM,[78,89,105,107,111] passive torque at the first sensation of stretch,[107,111] passive stiffness as a ratio between torque variation and ROM,[89,107,111] as well as tendon stiffness measured by tendon elongation.[81,109,110]

3.1.2. Methodological quality, risk of bias, and certainty about the evidence

Overall, the quality of the 65 included studies averaged 4.4 ± 1.0 on the PEDro scale (range: 3–8; acute: 4.2 ± 0.8, Supplementary Table 6; chronic: 4.9 ± 1.3, Supplementary Table 7). Depending on the investigated topic, the risk of bias assessment ranged from 4.0 ± 0.8 to 5.6 ± 1.3, indicating fair study quality[122] in all analysis groups.

Certainty of evidence was initially rated as high as almost all included studies were randomized controlled trials (RCTs). The level of evidence for acute (PEDro = 4.2 ± 0.8) and chronic effects (PEDro = 4.9 ± 1.3) had to be downgraded for risk of bias (1 level, PEDro score being fair). All other criteria did not lead to either down- or upgrading, resulting in an overall level of evidence considered to have moderate certainty for acute or chronic stimulation on ROM and stiffness.

3.1.3. Treatment characteristics

The included studies were conducted using different forms of vibration treatment, with 39 studies[57,58,61,63–77,82,83,85–87,90,91,93,95,101–103,106,109,110,113,117–121] using whole-body vibration platforms, 12 studies[59,60,78,79,92,94,100,107,111,114–116] using local vibration (with 2 percussive vibration), and 14 studies[62,80,82,84,88,89,96–99, 104,105,108,112] using vibration foam rollers. Thirteen of the included studies[69,74,85,90–92,100,102,106,111,113,119,121] performed stretching exercises with superimposed vibration either using a vibration platform (10/13) or a local vibration device (3/13). The exercise characteristics for acute studies are presented in Supplementary Table 4 and for chronic studies in Supplementary Table 5.

Of the 26 items that should be described according to the reporting guidelines for whole-body vibration studies,[46] the 65 included studies in this meta-analysis reported an average of 13.5 ± 3.1 of these items (range: 5–20, Supplementary Table 8).

The mean vibration frequency was 35.6 ± 25.8 Hz in 63 reporting studies[57–78, 80–87, 89–121] (range: 6.2–170.0 Hz),

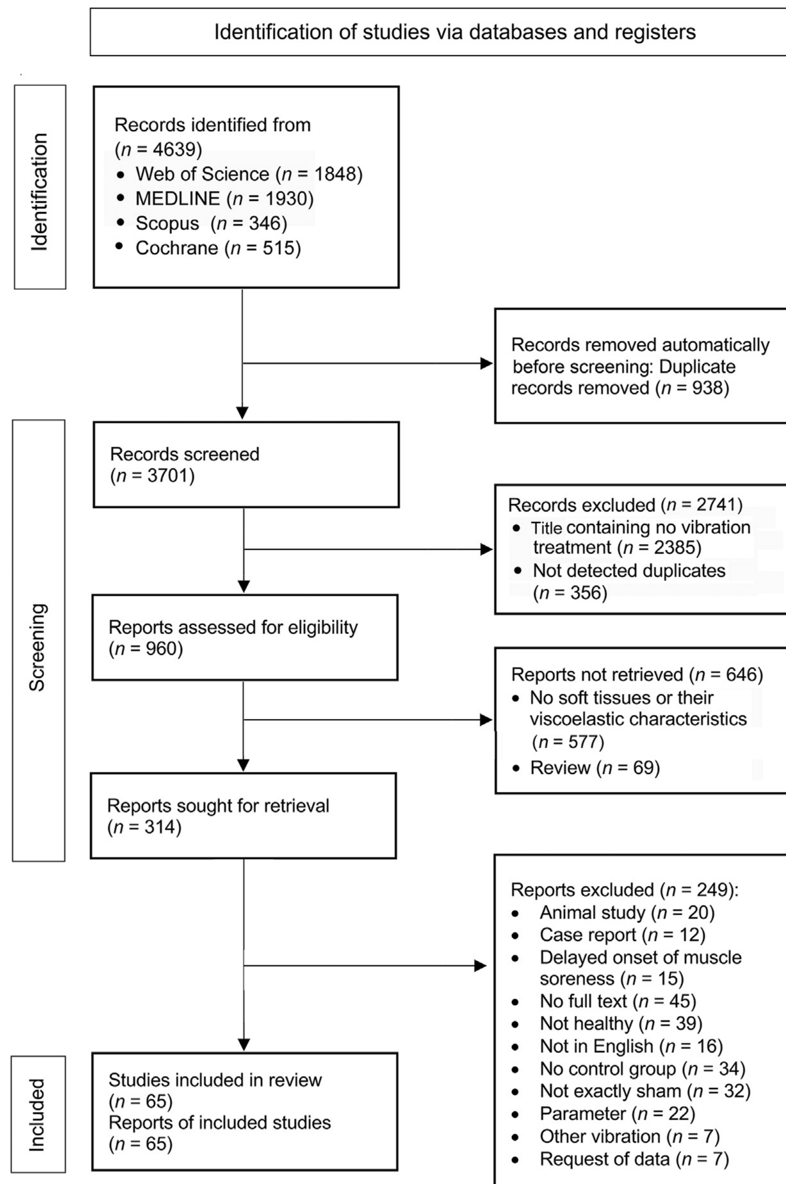

Fig. 1. Flowchart of the literature search.

mean vibration amplitude was 3.6 ± 2.3 mm in 46 reporting studies[57–59,61,63–78,82,83,85–87,90,91,95,100–104,106,107,109–111,113,115–121] (range: 0.01–9.36 mm), with 22 studies[59,63,64,67,68,71–73,76,77,86,87,90,101,103,109,110,115,116,118,120,121] presenting peak-to-peak amplitude with 4.4 ± 2.7 mm, and mean vibration acceleration was 13.2 ± 23.2 g in 13 reporting studies[57,61,64,67,71,73,80,103,106,107,109,110,120] (range: 2–98 g). Six studies[66,77,81,93,103,107] investigated more than one vibration condition. Vibration characteristics are presented in Supplementary Table 9.

3.2. *Quantitative analysis*

3.2.1. *Acute vibration effects on ROM*

Fig. 2 and Fig. 3 present pooled ES for acute effects of vibration, with respective exercise subgroups and method subgroups. Compared with the passive controls, the results show moderate magnitude flexibility increases (SMD = 0.71, $p < 0.001$ from 15 studies[59,62,69,79,88,94,99,100,104–107,111,112,114] with 28 ES). When attributing flexibility effects to vibration, the comparison to the sham condition revealed small magnitude effects (SMD = 0.20, $p < 0.001$ from 35 studies[57,58,62–67,69–71,75,77,84,85,88,90–93,95–98,100,102,104–106,108,111–113,119,121] with 56 ES). The passive control comparison subgroups showed significant effects of stretching with vibration (SMD = 0.62, $p = 0.023$) and local vibration (SMD = 0.95, $p = 0.007$). The comparison of stretching, foam rolling, and body-weight exercises with and without superimposed vibration (sham subgroups) revealed significant small-magnitude effects only for stretching (SMD = 0.32, $p = 0.006$) and trivial effects for body-weight exercises (SMD = 0.19, $p < 0.001$). Concerning methods used, ROM measurements with active and passive movements showed similar effects in control (SMD = 0.38, $p = 0.020$; SMD = 0.75, $p = 0.024$, respectively)

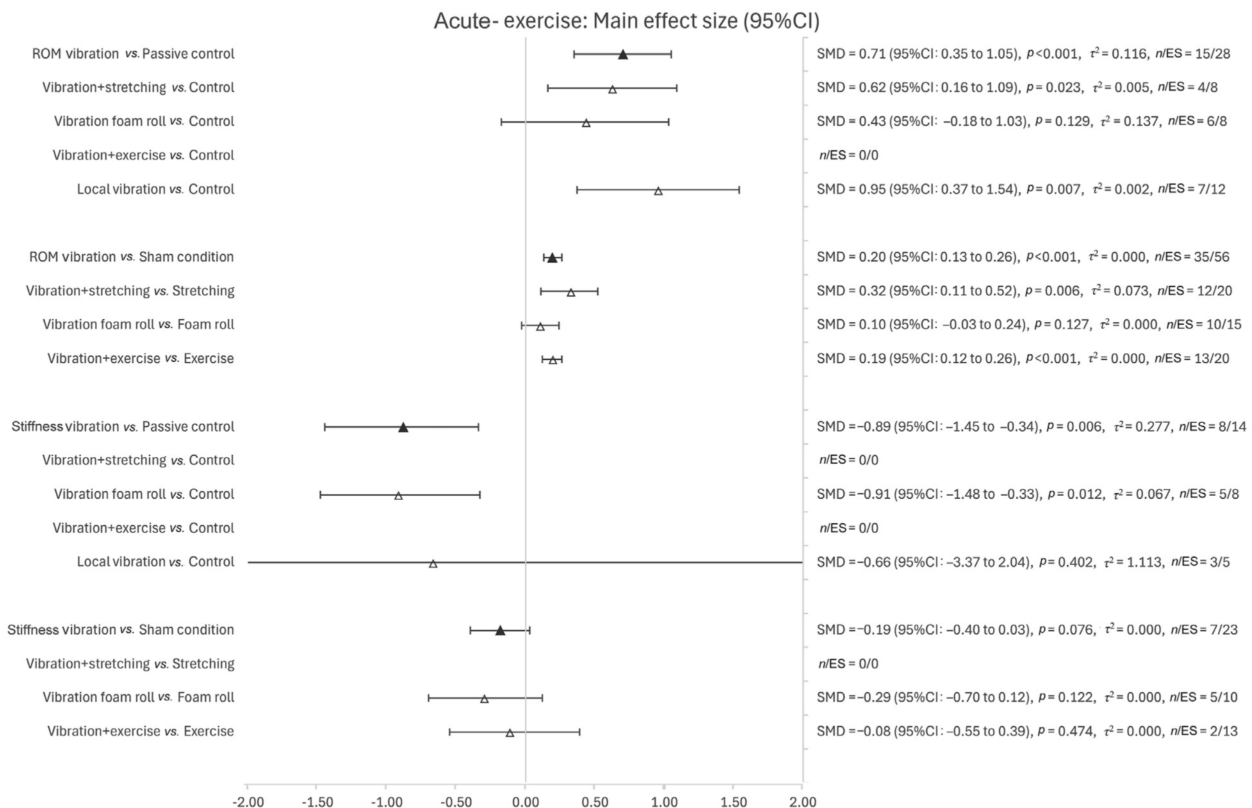

Fig. 2. ES pooling of acute vibration effects *vs.* passive control or sham conditions (▲), ES of subgroups based on vibration exercise (△) providing ES (SMD) with 95%CI, level of significance (p), heterogeneity (τ^2), as well as study number with the number of pre-post effects (n/ES) for r and stiffness. 95%CI = 95% confidence interval; ES = effect size; ROM = range of motion; SMD = standardized mean difference.

and sham comparisons (SMD = 0.22, $p < 0.001$; SMD = 0.32, $p = 0.006$).

3.2.2. Acute vibration effects on passive stiffness

Acutely, stiffness was largely reduced compared to a passive control (SMD = −0.89, $p = 0.006$), while the ES against sham condition was found to be trivial and non-significant (SMD = −0.19, $p = 0.076$). Subgroup analysis of exercises (Fig. 2) showed significant effects with large effects only for vibration foam rolling against control (SMD = −0.91, $p = 0.012$). Concerning measurement methods (Fig. 3), only indentation methods (myotonometry and hardness meter) (SMD = −0.97, $p = 0.018$) showed large significant effects of vibration treatment against non-intervened control comparisons.

3.2.3. Chronic vibration effects on ROM

Pooled ES for chronic effects of vibration are presented with respective exercise subgroups in Fig. 4 and method subgroups in Fig. 5. Compared to acute effects, only a few chronic studies matched this review's eligibility criteria. Seven studies[60,73,74,76,86,87,118] with 9 ES of vibration interventions showed moderate magnitude chronic ROM improvements (SMD = 0.64, $p = 0.043$) compared to non-intervened control conditions. Similar effects were obtained from 12 studies[67,71,72,74,78,82,83,89,101,113,117,120] with 43 ES when vibration training was compared with sham interventions (SMD = 0.65, $p < 0.001$, Fig. 6). Sham subgroups (Fig. 4) foam rolling (2 studies[82,89] with 5 ES) and body-weight exercises (8 studies[67,71,72,78,83,101,117,120] with 35 ES) with *vs.* without vibration reached the level of significance (SMD = 0.46, $p = 0.022$; and SMD = 0.66, $p < 0.001$, respectively).

3.2.4. Chronic vibration effects on passive stiffness

As only 2 studies[61,115] investigated chronic vibration effects on stiffness ($n = 1$ for passive control,[115] $n = 1$ for sham condition[61]), no analysis was performed due to lack of data quality (Fig. 5).

3.2.5. Meta-regression with vibration characteristics

Meta-regression with vibration characteristics (Supplementary Tables 10 and 11) showed that most vibration characteristics did not influence the study outcomes meaningfully. However, there were some significant regressions found for the effect of vibration frequency on acute ROM compared to control ($p < 0.001$) and sham ($p = 0.003$) as well as stiffness against control ($p = 0.014$). Additionally, there were effects of session duration (min) for acute stiffness compared to sham ($p = 0.036$) and total training duration (number of sessions × session duration in min) for chronic ROM effects compared to control ($p = 0.026$), but the ES were trivial (SMD: −0.049 to 0.007).

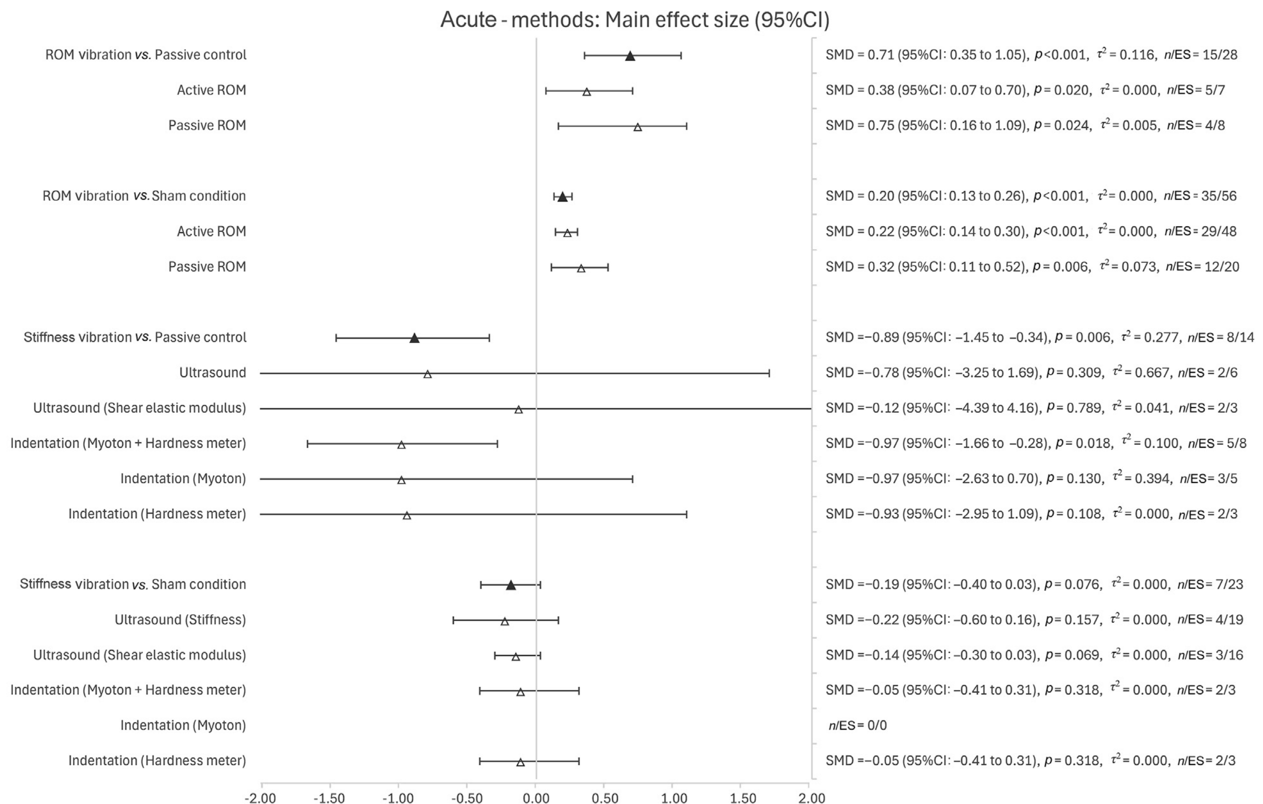

Fig. 3. ES pooling of acute vibration effects *vs.* passive control or sham conditions (▲), ES of subgroups based on measurement methods (△) providing ES (SMD) with 95%CI, level of significance (p), heterogeneity (τ^2), as well as study number with the number of pre-post effects (n/ES) for ROM and stiffness. 95%CI = 95% confidence interval; ES = effect size; ROM = range of motion; SMD = standardized mean difference.

3.3. Publication bias

Visual funnel plot inspection revealed no publication bias (Supplementary Fig. 1), which was confirmed by the Eggers regression test (ROM acute control: $p = 0.927$; ROM acute sham: $p = 0.476$; ROM chronic control: $p = 0.665$; ROM chronic sham: $p = 0.107$; stiffness acute control: $p = 0.221$; stiffness acute sham: $p = 0.710$).

4. Discussion

The current analysis showed that mechanical vibration interventions improved flexibility acutely compared to a passive control with trivial effects in addition to the same main exercise without vibration (sham). Passive stiffness was similarly affected in acute vibration interventions and might, therefore, act as a potential mediator for acute ROM increases.

When used over a period of weeks, superimposed vibration provided a significant merit of moderate magnitude compared to non-intervened controls and the respective sham condition. Due to insufficient outcomes, no chronic ES pooling was performed for passive stiffness. When considering the most common flexibility routines—stretching and foam rolling—additional vibration only induced a benefit in foam rolling when considering chronic effects. However, the effects of stretching could be improved acutely. The small coefficients of vibration parameters in meta-regression bring the relevance of moderators like frequency, amplitude, and duration of vibration into question.

4.1. Acute responses of ROM and underlying mechanisms

The current analysis contrasts with the findings of the Osawa and Oguma[35] meta-analysis, which found no additional effect of mechanical vibration on ROM in acute interventions ($p = 0.23$). However, we excluded 8 of their articles as they did not align with our defined inclusion criteria for the parameters used,[123–125] control,[126,127] or sham[128–130] groups. When splitting up the subgroups, they found a similar merit of superimposed vibration for stretching with 7 ES (SMD = 0.33, $p = 0.03$) but no significant difference in body-weight exercises with 3 ES (SMD = 0.17, $p = 0.47$), although both results used pooled data from acute and chronic studies. Wilke and colleagues[12] found no benefit of adding vibration to foam rolling (4 ES, $p = 0.32$), which was confirmed by the present analysis with 15 ES. As initially hypothesized, only stretching and body-weight exercises acutely benefit from superimposed vibration.

4.1.1. Neural factors

It has been proposed that the TVR could optimize flexibility when added to stretching effects.[34,129] This reflex is elicited by overstimulating Ia-afferent fibers, causing contractions during

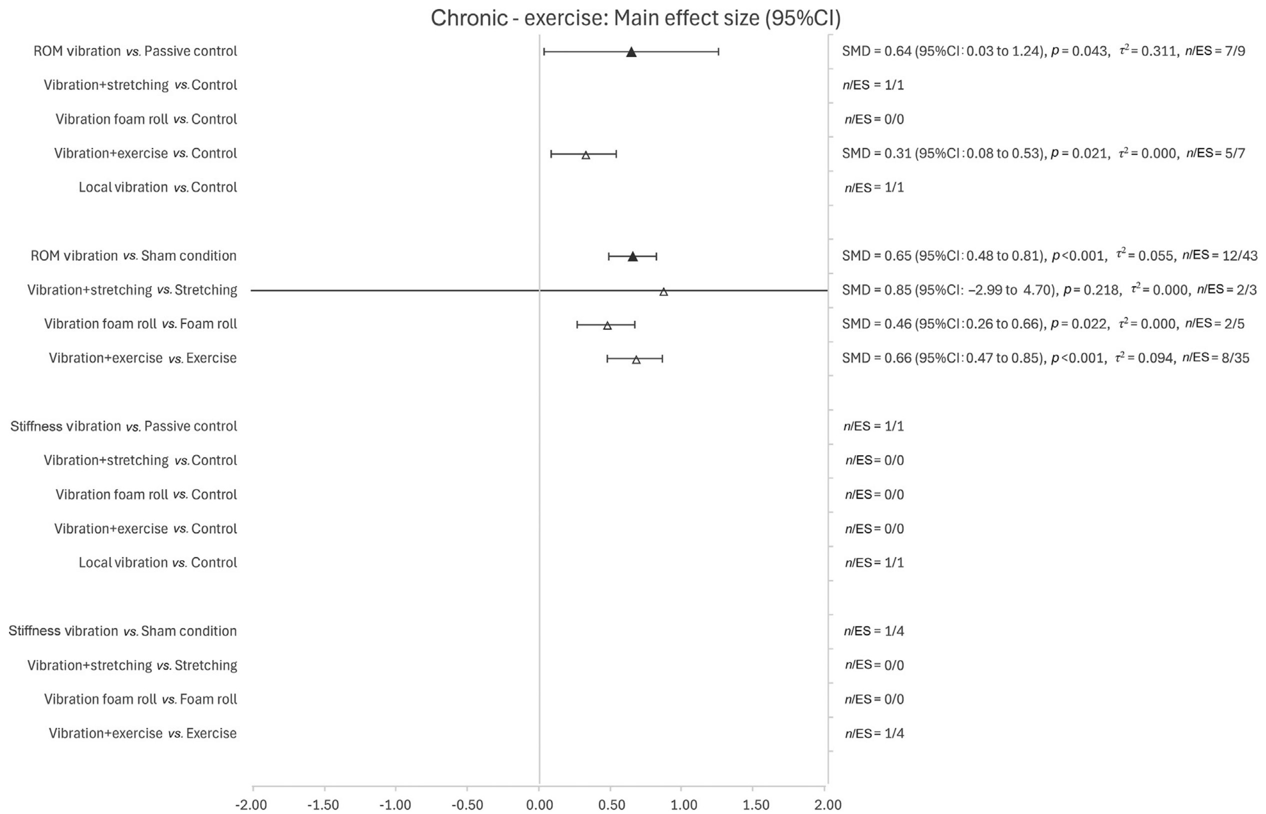

Fig. 4. ES pooling of chronic vibration effects *vs.* passive control or sham conditions (▲), ES of subgroups based on vibration exercise (△) providing ES (SMD) with 95%CI, level of significance (p), heterogeneity (τ^2), as well as study number with the number of pre-post effects (n/ES) for ROM and stiffness. 95%CI = 95% confidence interval; ES = effect size; ROM = range of motion; SMD = standardized mean difference.

stretching maneuvers. Both early animal research[17] and recent human studies[18] have shown that adding contractions to a regular stretching routine using electrical muscle stimulation at high muscle lengths can further increase flexibility. Further, the excitation of Golgi-tendon-organs (Ib-afferent fibers) due to vibration inhibits the stretch-reflex[131] as well as the Hofmann-reflex (H-reflex)[132] and is followed by muscle relaxation.[129,133] Referred to as the “vibration paradox”,[134] pathways relating to vibration are excited, while pathways responding to stretch are inhibited.[135]

4.1.2. Mechano-chemical signal conversion

Mechanical actuation via stretch or deformation can activate mechano-gated ion channels in all tissues and cell types, thereby converting mechanical stimulation into biochemical signals by opening ion channels—a process referred to as mechanotransduction.[136] Since their recent discovery,[25] Piezo channels have raised particular attention.[137–139] While Piezo-1 is, among other functions, essential for sensing tendon stretch, Piezo-2 transduces pain and senses proprioception.[138] Both channels were shown to respond to mechanical stimulation, with efficiency varying by stimulation frequency.[137]

4.1.3. Circulatory and thermoregulatory factors

While most acute and highly specific stretch responses such as H-reflexes and exteroceptive E-reflexes are expected to disappear within seconds,[140] the intervention specificity of acute ROM increases was recently challenged.[11] Warneke and colleagues[11] compared stretching and foam rolling to other types of active exercise (e.g., cycling, running, walking, resistance training) including mechanical vibration and found no significant acute differences in ROM, stiffness, or passive peak torque. The authors initially hypothesized that warm-up effects might be responsible for such responses. Vibration-induced flexibility increases are due to neural, circulatory, and thermoregulatory factors,[141] which are attributable to, among other things, increased blood circulation and heat generation.[22] A meta-analysis conducted by Nakano et al.[142] underlined this hypothesis and reported higher ROM increases after stretching with heat in both acute and chronic settings. Accordingly, friction[143] and the shock-absorbing mechanisms due to vibration within the muscle may transform mechanical energy via several pathways into heat.[144] While the exact impact of vibration on intramuscular temperature is still debated,[22] some research attributes this to increased muscle perfusion[22] and temperature.[145] Since improved blood circulation and heat generation are linked to enhanced flexibility,[141] it is plausible that vibration may also increase ROM.

4.1.4. Pain sensations

The pain threshold serves as a natural limit for stretching exercises.[146] Some authors suggest that physical activity,

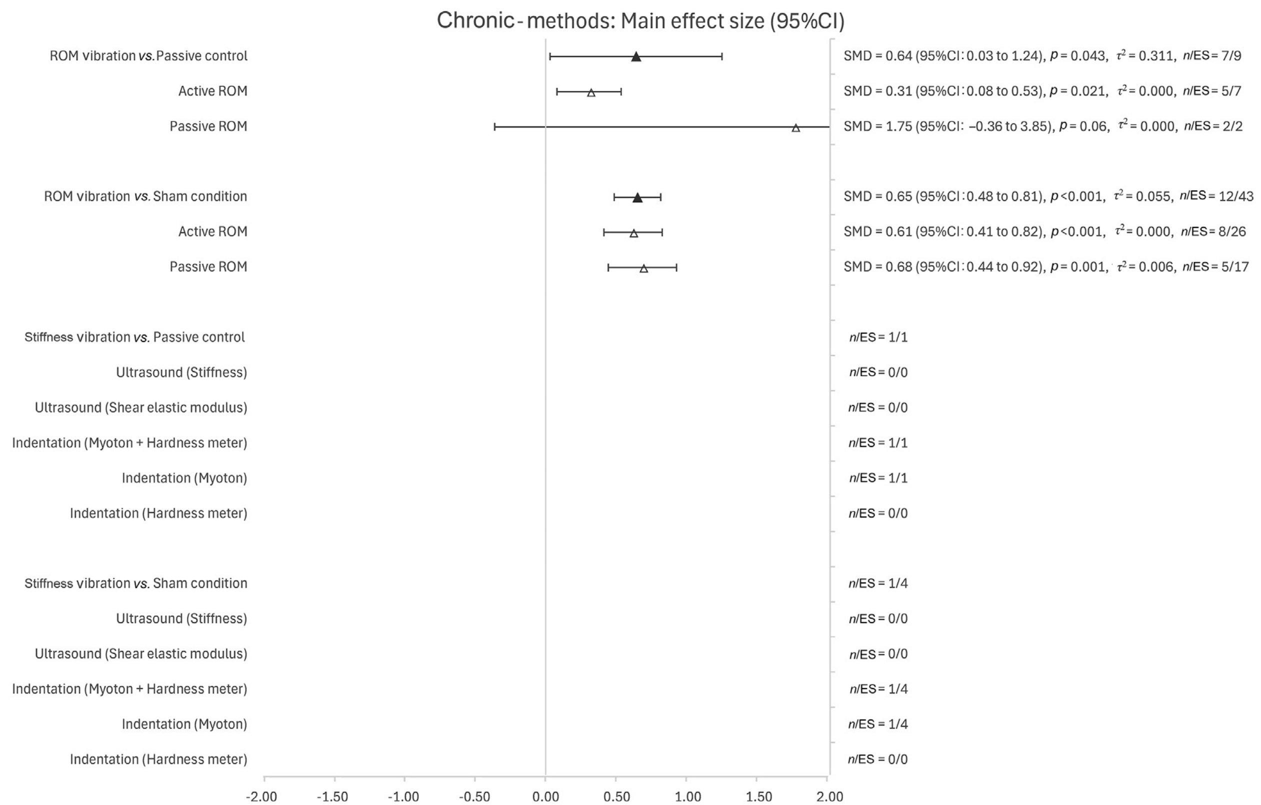

Fig. 5. ES pooling of chronic vibration effects *vs.* passive control or sham conditions (▲), ES of subgroups based on measurement methods (△) providing ES (SMD) with 95%CI, level of significance (p), heterogeneity (τ^2), as well as study number with the number of pre−post effects (n/ES) for ROM and stiffness. 95%CI = 95% confidence interval; ES = effect size; ROM = range of motion; SMD = standardized mean difference.

including vibration, can have an analgesic effect during and after its application.[129,147] Vibration can potentially alter pain sensation,[148,149] especially local vibration with high frequencies acting on the spinal gate control.[150] However, its effect on stretch-induced pain remains subjective[141] and requires further investigation. Despite aiming to explore the effects of vibration and the associated underlying mechanisms, we were unable to investigate its effects on passive torque parameters. The large number of studies ($n = 9$)[78,81,89,105,107–111] that included torque parameters in their investigations initially suggested that it might be possible to provide an improved perspective by pooling reported effects; however, the significant variation in methods required us to separate the study results into subgroups. These subgroups exhibited unacceptable differences in outcome between studies or within the same study, or there were too few studies to combine the results, which prevented us from quantifying these aspects in our analysis.

4.1.5. *Muscle stiffness*

Considering the muscle tuning theory,[30,151] several authors suggested that the musculoskeletal structures must quickly modulate muscle stiffness to cope with the vibratory waves.[152] In accordance with previously described potential warm-up effects, the main passive resistive component of muscle tissue is intramuscular collagen type I fibers and their fiber architecture,[153,154] which slightly extends[155] and decreases Young's modulus[156] with increasing physiological temperature. Accordingly, and to distinguish between specific vibration and general warm-up-related flexibility and stiffness responses, more specific and biological outcome investigations are warranted, especially since the vibration vs. sham comparison did not reach the level of significance and so currently provides no compelling evidence for specific vibration effects in acute stiffness adaptations.[11] Also, whether repeated stimulations might enhance this effect is unclear due to insufficient data. This remaining uncertainty is attributed to the lack of high-quality studies of underlying biological mechanisms as well as a very restricted number of studies that were eligible for inclusion.

4.2. *Chronic effects on ROM and underlying mechanisms*

In the long term, the results show a significant benefit of vibration on ROM. The effects of vibration were notably moderate to large when compared to a passive control, and the sham comparisons became significant for foam rolling and body-weight exercises. However, no additional benefit was reported for stretching.

4.2.1. *Specific exercises*

While RCTs provide valuable insights, it is important to interpret them correctly. When comparing interventions that

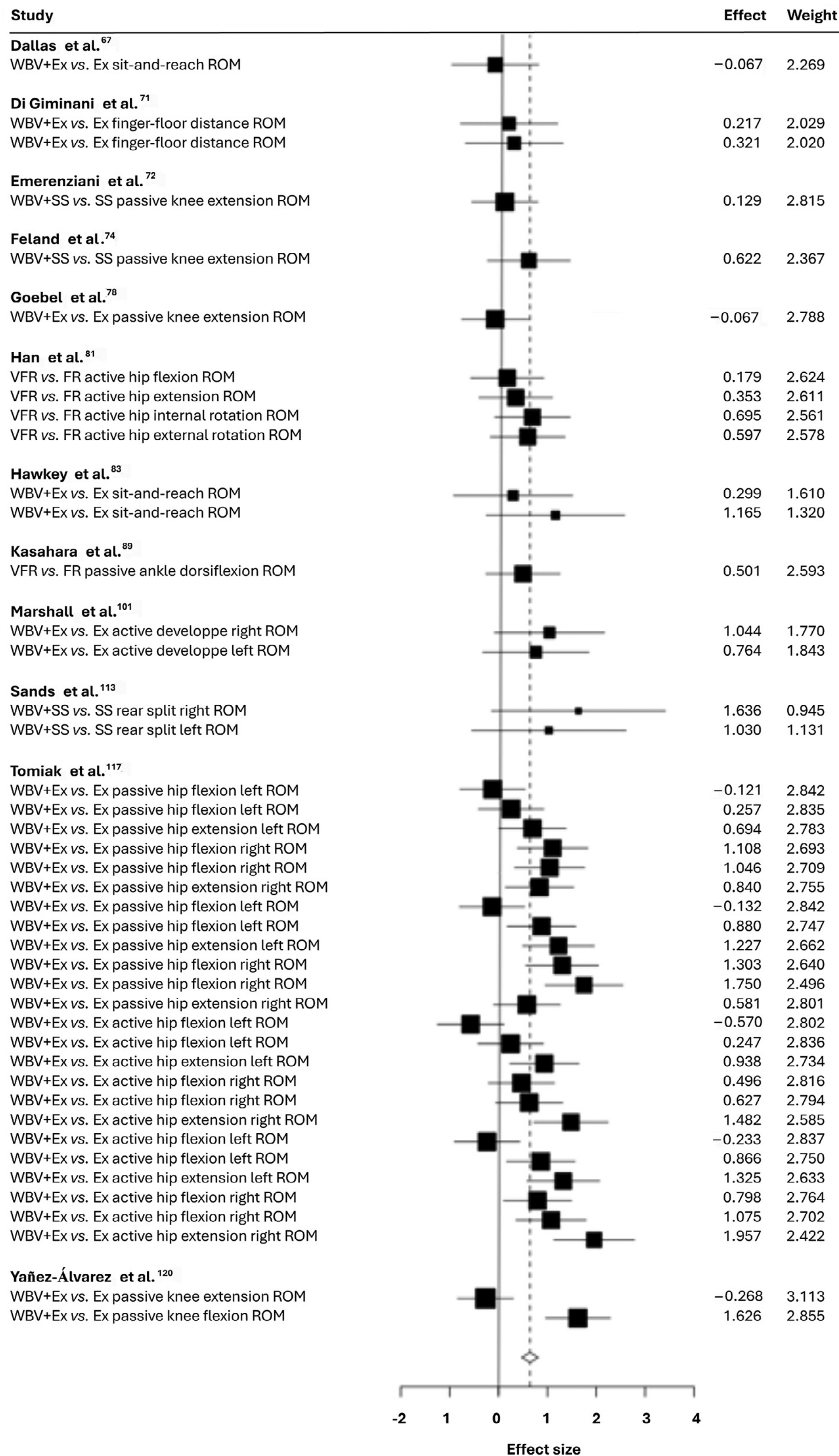

Fig. 6. Forest plot for chronic vibration interventions compared to a sham condition with ES = 0.65, $p < 0.001$ from 12 studies and 43 ES. ES = effect size; Ex = body-weight exercises; FR = foam rolling; ROM = range of motion; SS = static stretching; VFR = vibration foam rolling; WBV = whole-body vibration.

include vibration to a passive control, it is not possible to attribute these effects solely to vibration, rather they should be attributed to the combination of exercise and vibration employed. Thus, concluding vibration alone effectively improves ROM would be a misinterpretation of the findings, as these effects could be a result of overall enhanced performance levels due to activity or of the exercise itself upon which vibration was superimposed.[11] To evaluate the "pure" effect of vibration, one could consult chronic studies using only (local) vibration applications against a passive control—which are rare[60]—or separate combined interventions into exercise and vibration to assess the individual impact of both components. Compared to the sham condition, the benefits of superimposed vibration combined with stretching had no discernible benefits. However, there was a significant difference for foam rolling and body-weight exercises, both of which favored the vibration combination. While stretching as a stand-alone intervention is known to increase ROM chronically,[6,8] the findings for foam rolling are not as evident (1 analysis[9] revealed significant effects, 2 others did not[10,48]). This suggests that foam rolling alone did not provide a sufficient stimulus to enhance flexibility, and the improvements observed in this analysis could be attributed to the addition of vibration. A similar argument can be made for body-weight exercises, though the heterogeneity of exercise protocols complicates drawing a direct conclusion regarding the efficacy of improving flexibility on their own.

4.2.2. Mechanical tissue tension

Since flexibility increases are mainly attributed to neuromuscular and morphological aspects (e.g., stretching pain sensation and stiffness), whereby both are moderated by stretching[13,157] and resistance training,[7,20] Warneke et al.[55] discussed the relevance of mechanical tension with a potential effect on muscle length. Considering pain as a warning signal for harmful joint positions, structural adaptations that result in increased muscle lengths, thus serial sarcomere accumulation, could result in both delayed stretching pain as well as improved active ROM. Longitudinal hypertrophy was only found in animals, leaving evidence in humans speculative.[158,159] Nevertheless, assuming that superimposed active muscle contractions might provide an additional stimulus leading to more pronounced effects, vibration could be reasonably assumed to improve the effectivity of such interventions. Williams et al.[17] found immobilization of rabbits' hindlimbs to modulate the serial sarcomere number. In a stretched position, the number increased, and in a shortened position, the number decreased. Adding electrical stimulation—thus, contraction—increased the effectivity. It was therefore hypothesized that sarcomeres seek optimal contraction positions and, thus, increase in number when stretched due to insufficient overlap to form the actomyosin crossbridge, while too many sarcomeres in series could be assumed an unpreferable contraction precondition. While no direct evidence in humans exists, recent measures support this hypothesis, indicating higher effects on muscle thickness when electrical stimulation was superimposed to stretch.[18,19] Vibration elicits contractions due to the TVR[28,30] (as previously described in the acute section), and so it could be speculated that these effects, at least in part, account for the benefits of superimposed vibration in the sham comparison. However, following this hypothesis, it is surprising that no additional benefit from vibration was found for the stretching comparison in this meta-analysis.

4.2.3. Transmission

One possible explanation may be found in the transmission of vibration throughout the body: mechanical vibration and its transmission[160] are strongly dependent on vibration frequency[161] and how the vibration is imposed. Several approaches based on the concept of resonance have been explored.[162,163] According to this concept, if the excitation frequency of the stimulus matches the natural frequency of the resonator, its amplitude increases.[164] Stimulation at the resonant frequency was shown to elevate muscle activity[164,165] to counteract and thereby damp the vibration.[164] Here, mechanical responses of the muscles change in relation to posture,[165] with muscle length determining the TVR response.[166] This was shown by Wang et al,[163] as the resonance frequency of the patellar tendon (measured by its displacement in response to vibration frequencies from 15 Hz to 60 Hz with an accelerometer) increased with knee flexion, thus with tension on the tendon itself. Therefore, though hypothesized to be effective in a stretched position,[37,167] altered muscle activations might call for adapted vibration protocols to elevate effects.

Nevertheless, it should be noted that only 2 studies[74,113] were included in the stretching comparison, while most included chronic studies were investigated for other forms of exercise, including foam rolling and body-weight training. This is of special interest since Alizadeh et al.[20] suggested full ROM resistance training could also be described as dynamic stretching, which complicates the differentiation between several body-weight exercises and stretching.

4.2.4. Structural mechanisms

Structural adaptations (i.e., muscle elongation) can contribute to improved ROM. While not clarified in humans, animal studies have shown a serial sarcomere accumulation in response to diverse overload strategies.[159] Among other things, stretching has been reported to result in such longitudinal hypertrophy.[168] It has been suggested that the addition of sarcomeres elongates the muscle to enhance its contractility, as insufficient overlap of the actomyosin crossbridges negatively influences contraction forces.[169] To adapt to these unfavorable contraction preconditions, serial sarcomeres might thus be added to reduce the stretch of individual sarcomeres, thereby optimizing the contractile filament overlap.[169,170] Interestingly, muscle adaptations to intervention-induced changes in the contraction baseline were enhanced by superimposing muscle innervations. Since longitudinal hypertrophy is considered a structural adaptation, several articles highlighted an increase in protein synthesis in response to stretching[55,169] that is commonly associated with resistance training.[171] Synergizing underlying mechanisms were also highlighted in the

literature,[55,158] which is in accordance with Alizadeh's discussion[20] of the potential for classifying resistance training as a type of weighted dynamic stretching. Additionally, mechanical vibration can induce contractions at high muscle lengths (stretched muscle with decreased overlap between myofilaments[172,173]), leading to the hypothesis of similar physiological adaptations.

Interestingly, both stretching[158] as well as resistance training[171] produced an enhanced protein synthesis rate. In this regard, it is noteworthy that Warneke and colleagues[50] discussed the effects of a lengthened muscle fiber on stiffness and suggested that the increase in length (assuming a fixed distance between the origin and insertion of the muscle) could cause a reduction in passive stiffness (per the definition described in our Methods). The results on passive peak torque, also known as stretching pain, could be explained by an increased fiber length, considering that pain is a muscle warning against potential harm. Reaching high muscle length (thus minimal contractile filament overlap) that results in reduced force production capacity of the muscle[169] could cause potential harm to the unstable joint. If the muscle fiber is elongated via serial sarcomere addition, stretching pain would be induced at a higher muscle length, which could explain an increased passive peak torque. However, since the only marker for increased fiber length was an increased fascicle length/decreased pennation angle and a direct sarcomere count over the full muscle length seems impossible to establish in humans, these explanations remain theoretical. Currently, chronic ROM increases are most commonly attributed to decreases in tissue stiffness or increases in stretch tolerance.[8,49] While vibration may influence muscle function and neural control,[30] the high heterogeneity and substantial lack of high-quality and comparable study designs prevented the reasonable pooling of effects on stiffness and torque. Although some studies of single interventions suggest possible trends, further comparable research is strongly needed to conduct a robust meta-analysis of the effects of vibration. While several studies found no additional effects on passive torque parameters,[78,81,89,110] there is evidence that stiffness can be influenced by repeated interventions.[61,115]

4.3. Importance of vibration characteristics

The loading parameters of the stimulus, such as vibration characteristics, need to be precisely determined, applied, and controlled. Different types of vibration exposure may potentially affect the biological response in various ways.[134] Accordingly, several authors suggest that low frequencies of 8−15 Hz tend to reduce muscle tone, while higher frequencies of 20−35 Hz increase muscle tone,[174] though this relationship was never demonstrated with direct measurements of muscle stiffness.[152,175] Contrary to this assumption, our meta-regression suggests correlations of frequency with the ES of vibration against control for ROM ($\beta_0 = 0.007$) and stiffness ($\beta_0 = 0.007$), indicating that higher frequencies in certain ranges might increase the output. However, the comparison to the sham condition showed the opposite trend for ROM ($\beta_0 = -0.003$). Since all coefficients were rather small, we question the relevance of these findings. Furthermore, as the studies were performed with different vibration devices (Supplementary Table 9), this introduced heterogeneity, making precise comparisons and analyses difficult as further subgroups might be small and still diverse. The analysis of amplitude (mm) may also be biased as many included studies did not declare whether they used peak-to-peak amplitude.[57,58,61,65,66,69,70,74,75,78,81,83,91,95,100,105−107,111,113,117,119]

While a vibration frequency of 26 Hz was shown to elicit the greatest electromyography response for a given muscle,[176] most of the included studies used frequencies around 30 Hz (35.6 ± 25.8 Hz). Interestingly, Di Giminiani et al.[71] proposed that the optimum frequency for vibration varies between individuals, whereas Masud et al.[177] further argued that the optimal frequency is muscle-dependent. Therefore, frequency optimization in a whole-body vibration setting appears to be rather complex. However, the development of personalized vibration conditions might be beneficial to increase exercise outcomes.

4.4. Limitations of this meta-analysis

Although incorporating vibration into interventions with trivial to moderate effects was shown to improve ROM and passive stiffness, there are several limitations that restrict the generalizability of these findings. Consistent reporting of such studies would be essential and the community would benefit significantly by introducing a reporting scheme. As meta-analyses require high homogeneity regarding study designs to draw reasonable conclusions, the high heterogeneity—especially concerning stiffness and passive torque methods—may bias the final conclusion of our analysis. In this manner, the use of different forms of vibration used and inconsistent reporting of vibration characteristics counteract the results of the meta-regression. Therefore, the quality of included studies may be overrated by the PEDro score as important parameters of vibration studies cannot be considered here. It is noteworthy that the lack of blinding of study personnel was evident in most studies, and the absence of a general warm-up before the first measurement might have biased the studies' results, both of which highlight the need for a more standardized research design in exercise intervention studies. Furthermore, discussions about the possible mechanisms of the additional effects of vibration in exercise training are often hypothetical as there is lack of biological evidence, which calls for further research in this area. Finally, our meta-analysis was based on the assumption that vibration might add further improvement to an exercise (sham) condition. However, for this assumption to be valid, the basic exercise itself must have a positive effect on the investigated parameter. Therefore, we acknowledged the effects of the basic interventions (e.g., stretching) but they were not always affirmative, as was seen with foam rolling in chronic investigations. This raises the question of whether the observed improvements can be attributed to the addition of vibration and exercise or to the vibration alone.

5. Conclusion

In summary, vibration provides additional benefits upon single and repeated interventions. Note, though, that our conclusions only apply to the conditions tested in the set of studies considered here as excessive vibration has also been shown to have adverse health effects.[174,178] While the additive effect of an acute vibration intervention compared to the same intervention without vibration may be trivial, the addition might complement and increase a warm-up effect. Stiffness also appears to be similarly affected immediately, which may explain corresponding increases in ROM. In long-term (chronic) settings, superimposed vibration increases training outcomes, particularly flexibility. Given the ease of use for populations with compromised health, who find it difficult to undertake conventional exercises, mild but not excessive vibration might provide another avenue for increasing ROM if administered as described in the reviewed studies. This may have a positive influence on mobility and balance for older adults. Athletes in sports with the need for high flexibility (e.g., gymnastics, figure skating) or in sports where athletes typically struggle with their general ROM (e.g., running, road cycling) might also benefit from the additional stimulus, which provides a variation in their flexibility training routine and may lead to increased performance output.

Authors' contributions

DJ and KW developed the idea of the analysis, performed the data extraction, calculated the statistics, wrote the manuscript, and revised the study; AK and LHL were included in the quality assessment and provided valuable comments to the revision of the manuscript; DC assisted in the vibration characteristics assessment, reviewed literature, revised the manuscript, and performed the language check; JR reviewed the literature, provided his expertise for the definition of terms, and critically reviewed the manuscript; VV discussed and provided her expertise in reviewing the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

Availability of data and material

Original data can be provided upon reasonable request.

Supplementary materials

Supplementary materials associated with this article can be found in the online version at doi:10.1016/j.jshs.2025.101033.

References

1. Garber CE, Blissmer B, Deschenes MR, et al. American college of sports medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. *Med Sci Sports Exerc* 2011;**43**:1334–59.
2. Young WB. The use of static stretching in warm-up for training and competition. *Int J Sports Physiol Perform* 2007;**2**:212–6.
3. Behm DG, Chaouachi A. A review of the acute effects of static and dynamic stretching on performance. *Eur J Appl Physiol* 2011;**111**:2633–51.
4. Behm DG, Blazevich AJ, Kay AD, McHugh M. Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: A systematic review. *Appl Physiol Nutr Metab* 2016;**41**:1–11.
5. Koźlenia D, Domaradzki J. Prediction and injury risk based on movement patterns and flexibility in a 6-month prospective study among physically active adults. *PeerJ* 2021;**9**:e11399. doi:10.7717/peerj.11399.
6. Thomas E, Bianco A, Paoli A, Palma A. The relation between stretching typology and stretching duration: The effects on range of motion. *Int J Sports Med* 2018;**39**:243–54.
7. Afonso J, Ramirez-Campillo R, Moscão J, et al. Strength training versus stretching for improving range of motion: A systematic review and meta-analysis. *Healthcare (Basel)* 2021;**9**:427. doi:10.3390/healthcare9040427.
8. Konrad A, Alizadeh S, Daneshjoo A, et al. Chronic effects of stretching on range of motion with consideration of potential moderating variables: A systematic review with meta-analysis. *J Sport Health Sci* 2024;**13**:186–94.
9. Konrad A, Nakamura M, Tilp M, Donti O, Behm DG. Foam rolling training effects on range of motion: A systematic review and meta-analysis. *Sports Med* 2022;**52**:2523–35.
10. Pagaduan JC, Chang SY, Chang NJ. Chronic effects of foam rolling on flexibility and performance: A systematic review of randomized controlled trials. *Int J Environ Res Public Health* 2022;**19**:4315. doi:10.3390/ijerph19074315.
11. Warneke K, Plöschberger G, Lohmann LH, et al. Foam rolling and stretching do not provide superior acute flexibility and stiffness improvements compared to any other warm-up intervention: A systematic review with meta-analysis. *J Sport Health Sci* 2024;**13**:509–20.
12. Wilke J, Müller AL, Giesche F, Power G, Ahmedi H, Behm DG. Acute effects of foam rolling on range of motion in healthy adults: A systematic review with multilevel meta-analysis. *Sports Med* 2020;**50**:387–402.
13. Freitas SR, Mendes B, Le Sant G, Andrade RJ, Nordez A, Milanovic Z. Can chronic stretching change the muscle-tendon mechanical properties? A review. *Scand J Med Sci Sports* 2018;**28**:794–806.
14. Weppler CH, Magnusson SP. Increasing muscle extensibility: A matter of increasing length or modifying sensation? *Phys Ther* 2010;**90**:438–49.
15. Cai P, Liu L, Li H. Dynamic and static stretching on hamstring flexibility and stiffness: A systematic review and meta-analysis. *Heliyon* 2023;**9**: e18795. doi:10.1016/j.heliyon.2023.e18795.
16. Hosseini V, Gantenbein S, Avalos Vizcarra I, Schoen I, Vogel V. Stretchable silver nanowire microelectrodes for combined mechanical and electrical stimulation of cells. *Adv Healthc Mater* 2016;**5**:2045–54.
17. Williams PE, Catanese T, Lucey EG, Goldspink G. The importance of stretch and contractile activity in the prevention of connective tissue accumulation in muscle. *J Anat* 1988;**158**:109–14.
18. Mizuno T. Combined static stretching and electrical muscle stimulation induce greater changes in range of motion, passive torque, and tendon displacement compared with static stretching. *Sports (Basel)* 2023; **11**:10. doi:10.3390/sports11010010.
19. Mizuno T. Combined effects of static stretching and electrical stimulation on joint range of motion and muscle strength. *J Strength Cond Res* 2019;**33**:2694–703.
20. Alizadeh S, Daneshjoo A, Zahiri A, et al. Resistance training induces improvements in range of motion: A systematic review and meta-analysis. *Sports Med* 2023;**53**:707–22.
21. Luo J, McNamara B, Moran K. The use of vibration training to enhance muscle strength and power. *Sports Med* 2005;**35**:23–41.
22. Fuller JT, Thomson RL, Howe PR, Buckley JD. Effect of vibration on muscle perfusion: A systematic review. *Clin Physiol Funct Imaging* 2013;**33**:1–10.

23. Vay L, Gu C, McNaughton PA. Current perspectives on the modulation of thermo-trp channels: New advances and therapeutic implications. *Expert Rev Clin Pharmacol* 2010;**3**:687–704.
24. Vay L, Gu C, McNaughton PA. The thermo-trp ion channel family: Properties and therapeutic implications. *Br J Pharmacol* 2012;**165**:787–801.
25. Martinac B. 2021 Nobel Prize for mechanosensory transduction. *Biophys Rev* 2022;**14**:15–20.
26. Sá-Caputo D, Taiar R, Martins-Anjos E, et al. Does the mechano-biomodulation vibration lead to biological responses on human beings? *Ser Biomech* 2023;**37**:259219366. doi:10.7546/sb.01.02.2023.
27. Cardinale M, Wakeling J. Whole body vibration exercise: Are vibrations good for you? *Br J Sports Med* 2005;**39**:585–9.
28. Hagbarth KE, Eklund G. Tonic vibration reflexes (TVR) in spasticity. *Brain Res* 1966;**2**:201–3.
29. Burke D, Hagbarth KE, Lofstedt L, Wallin BG. The responses of human muscle spindle endings to vibration of non-contracting muscles. *J Physiol* 1976;**261**:673–93.
30. Cochrane DJ. The potential neural mechanisms of acute indirect vibration. *J Sports Sci Med* 2011;**10**:19–30.
31. Bishop B. Vibratory stimulation: Part I. Neurophysiology of motor responses evoked by vibratory stimulation. *Phys Ther* 1974;**54**:1273–82.
32. Lance J, Burke D, Andrews C. *The reflex effects of muscle vibration. Human reflexes, pathophysiology of motor systems, methodology of human reflexes*. Basel, Switzerland: Karger Publishers; 1973.
33. Đorđević D, Paunović M, Čular D, et al. Whole-body vibration effects on flexibility in artistic gymnastics−A systematic review. *Medicina (Kaunas)* 2022;**58**:595. doi:10.3390/medicina58050595.
34. Fowler BD, Palombo KTM, Feland JB, Blotter JD. Effects of whole-body vibration on flexibility and stiffness: A literature review. *Int J Exerc Sci* 2019;**12**:735–47.
35. Osawa Y, Oguma Y. Effects of vibration on flexibility: A meta-analysis. *J Musculoskelet Neuronal Interact* 2013;**13**:442–53.
36. Cochrane D. The sports performance application of vibration exercise for warm-up, flexibility and sprint speed. *Eur J Sport Sci* 2013;**13**:256–71.
37. Cardinale M, Lim J. Electromyography activity of vastus lateralis muscle during whole-body vibrations of different frequencies. *J Strength Cond Res* 2003;**17**:621–4.
38. Wager E, Wiffen PJ. Ethical issues in preparing and publishing systematic reviews. *J Evid Based Med* 2011;**4**:130–4.
39. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* 2021;**372**:n71. doi:10.1136/bmj.n71.
40. Bettany-Saltikov J. Learning how to undertake a systematic review: Part 1. *Nurs Stand* 2010;**24**:47–55.
41. Flemming K. Asking answerable questions. *Evid-Based Nu* 1998;**1**:36–7.
42. de Morton NA. The pedro scale is a valid measure of the methodological quality of clinical trials: A demographic study. *Aust J Physiother* 2009;**55**:129–33.
43. Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins M. Reliability of the PEDro scale for rating quality of randomized controlled trials. *Phys Ther* 2003;**83**:713–21.
44. Fernández-Castilla B, Declercq L, Jamshidi L, Beretvas N, Onghena P, Van den Noortgate W. Visual representations of meta-analyses of multiple outcomes: Extensions to forest plots, funnel plots, and caterpillar plots. *Methodology* 2020;**16**:299–315.
45. Atkins D, Best D, Briss PA, et al. Grading quality of evidence and strength of recommendations. *BMJ* 2004;**328**:1490. doi:10.1136/bmj.328.7454.1490.
46. van Heuvelen MJG, Rittweger J, Judex S, et al. Reporting guidelines for whole-body vibration studies in humans, animals and cell cultures: A consensus statement from an international group of experts. *Biology (Basel)* 2021;**10**:965. doi:10.3390/biology10100965.
47. Rauch F, Sievanen H, Boonen S, et al. Reporting whole-body vibration intervention studies: Recommendations of the international society of musculoskeletal and neuronal interactions. *J Musculoskelet Neuronal Interact* 2010;**10**:193–8.
48. Konrad A, Nakamura M, Behm DG. The effects of foam rolling training on performance parameters: A systematic review and meta-analysis including controlled and randomized controlled trials. *Int J Environ Res Public Health* 2022;**19**:11638. doi:10.3390/ijerph191811638.
49. Behm D. *The science and physiology of flexibility and stretching: Implications and applications in sport performance and health*. Abingdon on Thames: Routledge, Taylor and Francis Group; 2018.
50. Warneke K, Lohmann LH. Revisiting the stretch-induced force deficit: A systematic review with multilevel meta-analysis of acute effects. *J Sport Health Sci* 2024;**13**:805–19.
51. Gleim GW, McHugh MP. Flexibility and its effects on sports injury and performance. *Sports Med* 1997;**24**:289–99.
52. Magnusson SP. Passive properties of human skeletal muscle during stretch maneuvers. A review. *Scand J Med Sci Sports* 1998;**8**:65–77.
53. Lohmann LH, Zech A, Plöschberger G, Oraže M, Jochum D, Warneke K. Acute and chronic effects of stretching on balance: A systematic review with multilevel meta-analysis. *Front Med (Lausanne)* 2024;**11**:1451180. doi:10.3389/fmed.2024.1451180.
54. Fisher Z, Tipton E. Robumeta: An R-package for robust variance estimation in meta-analysis. *arXiv* 2015. doi:10.48550/arXiv.1503.02220.
55. Warneke K, Lohmann LH, Behm DG, et al. Effects of chronic static stretching on maximal strength and muscle hypertrophy: A systematic review and meta-analysis with meta-regression. *Sports Med Open* 2024;**10**:45. doi:10.1186/s40798-024-00706-8.
56. Faraone SV. Interpreting estimates of treatment effects: Implications for managed care. *P T* 2008;**33**:700–11.
57. Annino G, Iellamo F, Palazzo F, et al. Acute changes in neuromuscular activity in vertical jump and flexibility after exposure to whole body vibration. *Medicine (Baltimore)* 2017;**96**:e7629. doi:10.1097/MD.0000000000007629.
58. Apple S, Ehlert K, Hysinger P, Nash C, Voight M, Sells P. The effect of whole body vibration on ankle range of motion and the H-reflex. *N Am J Sports Phys Ther* 2010;**5**:33–9.
59. Atha J, Wheatley DW. Joint mobility changes due to low frequency vibration and stretching exercise. *Br J Sports Med* 1976;**10**:26–34.
60. Bakhtiary AH, Fatemi E, Khalili MA, Ghorbani R. Localised application of vibration improves passive knee extension in women with apparent reduced hamstring extensibility: A randomised trial. *J Physiother* 2011;**57**:165–71.
61. Basol F, Kara I, Saldiran TC. The effects of vibration exposure on lower-limb extensor muscles? Stiffness, elasticity, and strength responses in untrained young individuals: A randomized controlled trial. *J Sport Rehabil* 2023;**32**:415–23.
62. Cheatham SW, Stull KR, Kolber MJ. Comparison of a vibration roller and a nonvibration roller intervention on knee range of motion and pressure pain threshold: A randomized controlled trial. *J Sport Rehabil* 2019;**28**:39–45.
63. Cochrane DJ, Stannard SR. Acute whole body vibration training increases vertical jump and flexibility performance in elite female field hockey players. *Br J Sports Med* 2005;**39**:860–5.
64. Colson SS, Roffino S, Mutin-Carnino M, Carnino A, Petit PD. The effect of dynamic whole-body vibration warm-up on lower extremity performance. *Sci Sport* 2016;**31**:19–26.
65. Dallas G, Kirialanis P, Mellos V. The acute effect of whole body vibration training on flexibility and explosive strength of young gymnasts. *Biol Sport* 2014;**31**:233–7.
66. Dallas G, Paradisis G, Kirialanis P, Mellos V, Argitaki P, Smirniotou A. The acute effects of different training loads of whole body vibration on flexibility and explosive strength of lower limbs in divers. *Biol Sport* 2015;**32**:235–41.
67. Dallas G, Savvathi A, Dallas K, Maridaki M. The effect of 6-weeks whole body vibration on muscular performance on young non-competitive female artistic gymnasts. *Sci Gymnast J* 2019;**11**:151–62.
68. De Hoyo M, Carrasco L, Da Silva-Grigoletto ME, et al. Impact of an acute bout of vibration on muscle contractile properties, creatine kinase and lactate dehydrogenase response. *Eur J Sport Sci* 2013;**13**:666–73.

69. De Nardi M, Facheris C, Ruggeri P, La Torre A, Codella R. High-impact routines to ameliorate trunk and lower limbs flexibility in women. *Int J Sports Med* 2020;**41**:1039–46.
70. Despina T, George D, George T, et al. Short-term effect of whole-body vibration training on balance, flexibility and lower limb explosive strength in elite rhythmic gymnasts. *Hum Mov Sci* 2014;**33**:149–58.
71. Di Giminiani R, Manno R, Scrimaglio R, Sementilli G, Tihanyi J. Effects of individualized whole-body vibration on muscle flexibility and mechanical power. *J Sports Med Phys Fitness* 2010;**50**:139–51.
72. Emerenziani GP, Meucci M, Gallotta MC, Buzzachera CF, Guidetti L, Baldari C. Whole body vibration: Unsupervised training or combined with a supervised multi-purpose exercise for fitness? *J Sport Sci* 2014;**32**:1033–41.
73. Fagnani F, Giombini A, Di Cesare A, Pigozzi F, Di Salvo V. The effects of a whole-body vibration program on muscle performance and flexibility in female athletes. *Am J Phys Med Rehabil* 2006;**85**:956–62.
74. Feland JB, Hawks M, Hopkins JT, Hunter I, Johnson AW, Eggett DL. Whole body vibration as an adjunct to static stretching. *Int J Sports Med* 2010;**31**:584–9.
75. Gerakaki ME, Evangelidis PE, Tziortzis S, Paradisis GP. Acute effects of dynamic whole body vibration in well trained track & field sprinters. *J Phys Educ Sport* 2013;**13**:270–7.
76. Gerodimos V, Zafeiridis A, Chanou K, Karatrantou K, Dipla K. Whole-body vibration training in middle-aged females: Improving muscle flexibility and the power of lower limbs. *Sport Sci Health* 2015;**11**:287–94.
77. Gerodimos V, Zafeiridis A, Karatrantou K, Vasilopoulou T, Chanou K, Pispirikou E. The acute effects of different whole-body vibration amplitudes and frequencies on flexibility and vertical jumping performance. *J Sci Med Sport* 2010;**13**:438–43.
78. Goebel RT, Kleinöder H, Yue Z, Gosh R, Mester J. Effect of segment-body vibration on strength parameters. *Sports Med Open* 2015;**1**:14. doi:10.1186/s40798-015-0022-z.
79. Gordon CM, Lindner SM, Birbaumer N, Montoya P, Ankney RL, Andrasik F. Self-myofascial vibro-shearing: A randomized controlled trial of biomechanical and related changes in male breakdancers. *Sports Med Open* 2018;**4**:13. doi:10.1186/s40798-018-0128-1.
80. Griefahn A, Knicker A, von Piekartz H. Efficacy of foam rolling with additional vibration stimulation on the mobility of the thoracolumbar fascia. An observational study. *J Bodyw Mov Ther* 2021;**26**:84–93.
81. Han SW, Lee DY, Choi DS, Han B, Kim JS, Lee HD. Asynchronous alterations of muscle force and tendon stiffness following 8 weeks of resistance exercise with whole-body vibration in older women. *J Aging Phys Act* 2017;**25**:287–94.
82. Han SW, Lee YS, Lee DJ. The influence of the vibration form roller exercise on the pains in the muscles around the hip joint and the joint performance. *J Phys Ther Sci* 2017;**29**:1844–7.
83. Hawkey A, Griffiths K, Babraj J, Cobley JN. Whole-body vibration training and its application to age-related performance decrements: An exploratory analysis. *J Strength Cond Res* 2016;**30**:555–60.
84. Hsu FY, Tsai KL, Lee CL, Chang WD, Chang NJ. Effects of dynamic stretching combined with static stretching, foam rolling, or vibration rolling as a warm-up exercise on athletic performance in elite table tennis players. *J Sport Rehabil* 2021;**30**:198–205.
85. Jemni M, Mkaouer B, Marina M, Asllani A, Sands WA. Acute static vibration-induced stretching enhanced muscle viscoelasticity but did not affect maximal voluntary contractions in footballers. *J Strength Cond Res* 2014;**28**:3105–14.
86. Karatrantou K, Bilios P, Bogdanis GC, Ioakimidis P, Soulas E, Gerodimos V. Effects of whole-body vibration training frequency on neuromuscular performance: A randomized controlled study. *Biol Sport* 2019;**36**:273–81.
87. Karatrantou K, Gerodimos V, Dipla K, Zafeiridis A. Whole-body vibration training improves flexibility, strength profile of knee flexors, and hamstrings-to-quadriceps strength ratio in females. *J Sci Med Sport* 2013;**16**:477–81.
88. Kasahara K, Konrad A, Yoshida R, et al. Comparison of the prolonged effects of foam rolling and vibration foam rolling interventions on passive properties of knee extensors. *J Sports Sci Med* 2022;**21**:580–5.
89. Kasahara K, Konrad A, Yoshida R, et al. Comparison between 6-week foam rolling intervention program with and without vibration on rolling and non-rolling sides. *Eur J Appl Physiol* 2022;**122**:2061–70.
90. Kemertzis MA, Lythgo ND, Morgan DL, Galea MP. Ankle flexors produce peak torque at longer muscle lengths after whole-body vibration. *Med Sci Sports Exerc* 2008;**40**:1977–83.
91. Kinser AM, Ramsey MW, O'Bryant HS, Ayres CA, Sands WA, Stone MH. Vibration and stretching effects on flexibility and explosive strength in young gymnasts. *Med Sci Sports Exerc* 2008;**40**:133–40.
92. Ko MG, Lee MM, Song CH. A comparison of the effects of different stretching methods on flexibility, muscle activity, and pain threshold in ballet dancers; A preliminary randomized controlled trial. *J Bodyw Mov Ther* 2020;**24**:354–60.
93. Komiya M, Urabe Y, Sasadai J, Fujishita H, Sakai S, Maeda N. The effects of two different whole-body-vibration frequencies on ankle dorsiflexion angle, vertical jump height, and postural stability after landing. *Isokinet Exerc Sci* 2019;**27**:267–74.
94. Konrad A, Glashüttner C, Reiner MM, Bernsteiner D, Tilp M. The acute effects of a percussive massage treatment with a hypervolt device on plantar flexor muscles' range of motion and performance. *J Sports Sci Med* 2020;**19**:690–4.
95. Kurt C, Pekunlu E. Acute effect of whole body vibration on isometric strength, squat jump, and flexibility in well-trained combat athletes. *Biol Sport* 2015;**32**:115–22.
96. Lee CL, Chu IH, Lyu BJ, Chang WD, Chang NJ. Comparison of vibration rolling, nonvibration rolling, and static stretching as a warm-up exercise on flexibility, joint proprioception, muscle strength, and balance in young adults. *J Sports Sci* 2018;**36**:2575–82.
97. Lim JH, Park CB. The immediate effects of foam roller with vibration on hamstring flexibility and jump performance in healthy adults. *J Exerc Rehabil* 2019;**15**:50–4.
98. Lim JN, Park CB, Kim BG. The effects of vibration foam roller applied to hamstring on the quadriceps electromyography activity and hamstring flexibility. *J Exerc Rehabil* 2019;**15**:560–5.
99. Lin WC, Lee CL, Chang NJ. Acute effects of dynamic stretching followed by vibration foam rolling on sports performance of badminton athletes. *J Sports Sci Med* 2020;**19**:420–8.
100. Maeda N, Urabe Y, Kotoshiba S, et al. Acute effects of local vibration stretching on ankle range of motion, vertical jump performance and dynamic balance after landing. *Isokinet Exerc Sci* 2021;**29**:139–45.
101. Marshall LC, Wyon MA. The effect of whole-body vibration on jump height and active range of movement in female dancers. *J Strength Cond Res* 2012;**26**:789–93.
102. McNeal JR, Edgerly S, Sands WA, Kawaguchi J. Acute effects of vibration-assisted stretching are more evident in the non-dominant limb. *Eur J Sport Sci* 2011;**11**:45–50.
103. Muanjai P, Haas C, Sies W, et al. Effect of whole-body vibration frequency on muscle tensile state during graded plantar flexor isometric contractions. *J Exerc Sci Fit* 2023;**21**:405–15.
104. Nakamura M, Konrad A, Kasahara K, et al. The combined effect of static stretching and foam rolling with or without vibration on the range of motion, muscle performance, and tissue hardness of the knee extensor. *J Strength Cond Res* 2023;**37**:322–7.
105. Nakamura M, Sato S, Kiyono R, et al. Comparison between foam rolling with and without vibration on passive and active plantar flexor muscle properties. *J Strength Cond Res* 2022;**36**:3339–44.
106. Olivares-Arancibia J, Solis-Urra P, Rodriguez-Rodriguez F, et al. A single bout of whole-body vibration improves hamstring flexibility in university athletes: A randomized controlled trial. *J Hum Sport Exerc* 2018;**13**:776–88.
107. Pereira BM, Magalhaes FA, Lacerda ACR, Andrade AGP, Peixoto GHD, Chagas MH. Comparison of four local vibratory stimuli on mechanical and sensorial variables related to muscle-tendon unit response. *Transl Sports Med* 2020;**3**:440–6.
108. Reiner MM, Glashüttner C, Bernsteiner D, et al. A comparison of foam rolling and vibration foam rolling on the quadriceps muscle function and mechanical properties. *Eur J Appl Physiol* 2021;**121**:1461–71.

109. Rieder F, Wiesinger HP, Kösters A, Müller E, Seynnes OR. Immediate effects of whole body vibration on patellar tendon properties and knee extension torque. *Eur J Appl Physiol* 2016;**116**:553–61.
110. Rieder F, Wiesinger HP, Kösters A, Müller E, Seynnes OR. Whole-body vibration training induces hypertrophy of the human patellar tendon. *Scand J Med Sci Sports* 2016;**26**:902–10.
111. Rodrigues SA, Rabelo AS, Couto BP, et al. Acute effects of single bout of stretching exercise and mechanical vibration in hamstring muscle. *J Exerc Physiol Online* 2017;**20**:46–57.
112. Ruggieri RM, Coburn JW, Galpin AJ, Costa PB. Effects of a vibrating foam roller on ipsilateral and contralateral neuromuscular function and the hamstrings-to-quadriceps ratios. *Int J Exerc Sci* 2021;**14**:304–23.
113. Sands WA, McNeal JR, Stone MH, Russell EM, Jemni M. Flexibility enhancement with vibration: Acute and long-term. *Med Sci Sports Exerc* 2006;**38**:720–5.
114. Skinner B, Dunn L, Moss R. The acute effects of Theragun™ percussive therapy on viscoelastic tissue dynamics and hamstring group range of motion. *J Sports Sci Med* 2023;**22**:496–501.
115. Souron R, Lapole T. Eight weeks of local vibration training do not increase tibialis anterior muscle stiffness evaluated by supersonic shear imaging. *IRBM* 2018;**39**:291–4.
116. Souron R, Zambelli A, Espeit L, Besson T, Cochrane DJ, Lapole T. Active versus local vibration warm-up effects on knee extensors stiffness and neuromuscular performance of healthy young males. *J Sci Med Sport* 2019;**22**:206–11.
117. Tomiak T, Niewiadomska MA, Zasada M, Melnik LJ, Mishchenko VS, Sawczyn S. The long lasting effects of whole body rotation vibration in a fitness exercise program on flexibility and motor coordination in young females. *Balt J Health Phys A* 2012;**4**:221–30.
118. Tseng SY, Lai CL, Ko CP, Chang YK, Fan HC, Wang CH. The effectiveness of whole-body vibration and heat therapy on the muscle strength, flexibility, and balance abilities of elderly groups. *Int J Environ Res Public Health* 2023;**20**:1650. doi:10.3390/ijerph20021650.
119. Tsuji T, Kitano N, Tsunoda K, Himori E, Okura T, Tanaka K. Short-term effects of whole-body vibration on functional mobility and flexibility in healthy, older adults: A randomized crossover study. *J Geriatr Phys Ther* 2014;**37**:58–64.
120. Yañez-Álvarez A, Bermúdez-Pulgarín B, Hernández-Sánchez S, Albornoz-Cabello M. Effects of exercise combined with whole body vibration in patients with patellofemoral pain syndrome: A randomised-controlled clinical trial. *BMC Musculoskelet Disord* 2020;**21**:582. doi:10.1186/s12891-020-03599-2.
121. Yang WW, Liu C, Shiang TY. Warm-up effects from concomitant use of vibration and static stretching after cycling. *J Sports Med Phys Fitness* 2017;**57**:362–8.
122. Cashin AG, McAuley JH. Clinimetrics: Physiotherapy evidence database (PEDro) scale. *J Physiother* 2020;**66**:59. doi:10.1016/j.jphys.2019.08.005.
123. Siu PM, Tam BT, Chow DH, et al. Immediate effects of 2 different whole-body vibration frequencies on muscle peak torque and stiffness. *Arch Phys Med Rehabil* 2010;**91**:1608–15.
124. George D, Vasilis K, Vasilis M, Giorgos P. Acute effect of whole-body vibration combined with stretching on bridge performance in artistic gymnasts. *Biol Exerc* 2012;**8**:5–15.
125. Herda TJ, Ryan ED, Smith AE, et al. Acute effects of passive stretching *vs*. vibration on the neuromuscular function of the plantar flexors. *Scand J Med Sci Sports* 2009;**19**:703–13.
126. Bosco C, Dellisanti F, Fucci A, et al. The effect of whole body vibration on explosive power, speed endurance and extensibility of soccer players leg muscles. *Med dello sport* 2001;**54**:287–93.
127. Lapole T, Pérot C. Effects of repeated achilles tendon vibration on triceps surae stiffness and reflex excitability. *J Electromyogr Kinesiol* 2011;**21**:87–94.
128. Cronin J, Nash M, Whatman C. The acute effects of hamstring stretching and vibration on dynamic knee joint range of motion and jump performance. *Phys Ther Sport* 2008;**9**:89–96.
129. Issurin VB, Liebermann DG, Tenenbaum G. Effect of vibratory stimulation training on maximal force and flexibility. *J Sports Sci* 1994;**12**:561–6.
130. Jacobs PL, Burns P. Acute enhancement of lower-extremity dynamic strength and flexibility with whole-body vibration. *J Strength Cond Res* 2009;**23**:51–7.
131. Desmedt JE, Godaux E. Mechanism of the vibration paradox: Excitatory and inhibitory effects of tendon vibration on single soleus muscle motor units in man. *J Physiol* 1978;**285**:197–207.
132. Martin BJ, Roll JP, Gauthier GM. Inhibitory effects of combined agonist and antagonist muscle vibration on H-reflex in man. *Aviat Space Environ Med* 1986;**57**:681–7.
133. Fox EL, Mathews DK. *The physiological basis of physical education and athletics*. Philadelphia, PE: Saunders College Pub; 1981.
134. Jordan MJ, Norris SR, Smith DJ, Herzog W. Vibration training: An overview of the area, training consequences, and future considerations. *J Strength Cond Res* 2005;**19**:459–66.
135. Flieger J, Karachalios T, Khaldi L, Raptou P, Lyritis G. Mechanical stimulation in the form of vibration prevents postmenopausal bone loss in ovariectomized rats. *Calcif Tissue Int* 1998;**63**:510–4.
136. Vogel V, Sheetz M. Local force and geometry sensing regulate cell functions. *Nat Rev Mol Cell Biol* 2006;**7**:265–75.
137. Lewis AH, Cui AF, McDonald MF, Grandl J. Transduction of repetitive mechanical stimuli by Piezo1 and Piezo2 ion channels. *Cell Rep* 2017;**19**:2572–85.
138. Savadipour A, Palmer D, Ely EV, et al. The role of Piezo ion channels in the musculoskeletal system. *Am J Physiol Cell Physiol* 2023;**324**:C728–40.
139. Tadge T, Pattewar A, More N, Babu SS, Velyutham R, Kapusetti G. The role of Piezo1 and Piezo2 proteins in tissue engineering: A comprehensive review. *Eng Regen* 2024;**5**:170–85.
140. Behm DG, Kay AD, Trajano GS, Blazevich AJ. Mechanisms underlying performance impairments following prolonged static stretching without a comprehensive warm-up. *Eur J Appl Physiol* 2021;**121**:67–94.
141. Issurin V. Vibrations and their applications in sport. A review. *J Sports Med Phys Fitness* 2005;**45**:324–36.
142. Nakano J, Yamabayashi C, Scott A, Reid WD. The effect of heat applied with stretch to increase range of motion: A systematic review. *Phys Ther Sport* 2012;**13**:180–8.
143. Issurin VB, Tenenbaum G. Acute and residual effects of vibratory stimulation on explosive strength in elite and amateur athletes. *J Sports Sci* 1999;**17**:177–82.
144. Wakeling JM, Nigg BM, Rozitis AI. Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. *J Appl Physiol* 2002;**93**:1093–103.
145. Cochrane DJ, Stannard SR, Sargeant AJ, Rittweger J. The rate of muscle temperature increase during acute whole-body vibration exercise. *Eur J Appl Physiol* 2008;**103**:441–8.
146. Alter MJ. *Science of flexibility*. Champaign, IL: Human Kinetics; 2004.
147. Kurt C. Alternative to traditional stretching methods for flexibility enhancement in well-trained combat athletes: local vibration versus whole-body vibration. *Biol Sport* 2015;**32**:225–33.
148. Lundeberg T, Nordemar R, Ottoson D. Pain alleviation by vibratory stimulation. *Pain* 1984;**20**:25–44.
149. Pantaleo T, Duranti R, Bellini F. Effects of vibratory stimulation on muscular pain threshold and blink response in human subjects. *Pain* 1986;**24**:239–50.
150. Casale R, Hansson P. The analgesic effect of localized vibration: A systematic review. Part 1: The neurophysiological basis. *Eur J Phys Rehabil Med* 2022;**58**:306–15.
151. Nigg BM. Impact forces in running. *Current Opinion in Orthopaedics* 1997;**8**:43–7.
152. Cardinale M, Bosco C. The use of vibration as an exercise intervention. *Exerc Sport Sci Rev* 2003;**31**:3–7.
153. Taylor DC, Dalton Jr JD, Seaber AV, Garrett Jr WE. Viscoelastic properties of muscle-tendon units. The biomechanical effects of stretching. *Am J Sports Med* 1990;**18**:300–9.
154. Fratzl P, Misof K, Zizak I, Rapp G, Amenitsch H, Bernstorff S. Fibrillar structure and mechanical properties of collagen. *J Struct Biol* 1998;**122**:119–22.
155. Warren CG, Lehmann JF, Koblanski JN. Heat and stretch procedures: An evaluation using rat tail tendon. *Arch Phys Med Rehabil* 1976;**57**:122–6.

156. Gevorkian SG, Allahverdyan AE, Gevorgyan DS, Simonian AL. Thermal (in)stability of type I collagen fibrils. *Phys Rev Lett* 2009;**102**:048101. doi:10.1103/PhysRevLett.102.048101.
157. Takeuchi K, Nakamura M, Fukaya T, Konrad A, Mizuno T. Acute and long-term effects of static stretching on muscle-tendon unit stiffness: A systematic review and meta-analysis. *J Sports Sci Med* 2023;**22**:465–75.
158. Warneke K, Lohmann LH, Lima CD, et al. Physiology of stretch-mediated hypertrophy and strength increases: A narrative review. *Sports Med* 2023;**53**:2055–75.
159. Kruse A, Rivares C, Weide G, Tilp M, Jaspers RT. Stimuli for adaptations in muscle length and the length range of active force exertion—A narrative review. *Front Physiol* 2021;**12**:742034. doi:10.3389/fphys.2021.742034.
160. Friesenbichler B, Lienhard K, Vienneau J, Nigg BM. Vibration transmission to lower extremity soft tissues during whole-body vibration. *J Biomech* 2014;**47**:2858–62.
161. Cidem M, Karacan I, Cakar HI, et al. Vibration parameters affecting vibration-induced reflex muscle activity. *Somatosens Mot Res* 2017;**34**:47–51.
162. Wakeling JM, Nigg BM. Modification of soft tissue vibrations in the leg by muscular activity. *J Appl Physiol (1985)* 2001;**90**:412–20.
163. Wang TG, Hsiao TY, Wang CL, Shau YW. Resonance frequency in patellar tendon. *Scand J Med Sci Sports* 2007;**17**:535–8.
164. Wakeling JM, Nigg BM, Rozitis AI. Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. *J Appl Physiol (1985)* 2002;**93**:1093–103.
165. Fratini A, La Gatta A, Bifulco P, Romano M, Cesarelli M. Muscle motion and EMG activity in vibration treatment. *Med Eng Phys* 2009;**31**:1166–72.
166. Nordin M, Hagbarth KE. Effects of preceding movements and contractions on the tonic vibration reflex of human finger extensor muscles. *Acta Physiol Scand* 1996;**156**:435–40.
167. Ritzmann R, Gollhofer A, Kramer A. The influence of vibration type, frequency, body position and additional load on the neuromuscular activity during whole body vibration. *Eur J Appl Physiol* 2013;**113**:1–11.
168. Warneke K, Freund PA, Schiemann S. Long-lasting stretching induces muscle hypertrophy: A meta-analysis of animal studies. *J Sci Sport Exerc* 2023;**5**:289–301.
169. Warneke K, Behm DG, Alizadeh S, Hillebrecht M, Konrad A, Wirth K. Discussing conflicting explanatory approaches in flexibility training under consideration of physiology: A narrative review. *Sports Med* 2024;**54**:1785–99.
170. Tabary JC, Tabary C, Tardieu C, Tardieu G, Goldspink G. Physiological and structural changes in the cat's soleus muscle due to immobilization at different lengths by plaster casts. *J Physiol* 1972;**224**:231–44.
171. Wackerhage H, Schoenfeld BJ, Hamilton DL, Lehti M, Hulmi JJ. Stimuli and sensors that initiate skeletal muscle hypertrophy following resistance exercise. *J Appl Physiol (1985)* 2019;**126**:30–43.
172. Leonard TR, Herzog W. Regulation of muscle force in the absence of actin-myosin-based cross-bridge interaction. *Am J Physiol Cell Physiol* 2010;**299**:C14–20.
173. Appleton B. *Stretching and flexibility everything you never wanted to know*. Available at: https://judoinfo.com/wp-content/uploads/2016/07/pdf/stretching.pdf. [accessed 01.06.2024].
174. Rittweger J. *Manual of vibration exercise and vibration therapy*. Basel: Springer International Publishing; 2020.
175. Cronin JB, Oliver M, McNair PJ. Muscle stiffness and injury effects of whole body vibration. *Phys Ther Sport* 2004;**5**:68–74.
176. Cochrane DJ, Stannard SR, Walmsely A, Firth EC. The acute effect of vibration exercise on concentric muscular characteristics. *J Sci Med Sport* 2008;**11**:527–34.
177. Masud AA, Shen CL, Luk HY, Chyu MC. Impact of local vibration training on neuromuscular activity, muscle cell, and muscle strength: A review. *Crit Rev Biomed Eng* 2022;**50**:1–17.
178. International Standard for Standardisation. *ISO 2631-1 mechanical vibration and shock—Evaluation of human exposure to whole-body vibration—Part 1: General requirements*. Available at: https://www.iso.org/standard/7612.html. [accessed 01.06.2024].