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Review

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

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Abstract

Background: Acute improvement in range of motion (ROM) is a widely reported effect of stretching and foam rolling, which is commonly explained by changes in pain threshold and/or musculotendinous stiffness. Interestingly, these effects were also reported in response to various other active and passive interventions that induce responses such as enhanced muscle temperature. Therefore, we hypothesized that acute ROM enhancements could be induced by a wide variety of interventions other than stretching or foam rolling that promote an increase in muscle temperature.
Methods: After a systematic search in PubMed, Web of Science, and SPORTDiscus databases, 38 studies comparing the effects of stretching and foam rolling with several other interventions on ROM and passive properties were included. These studies had 1134 participants in total, and the data analysis resulted in 140 effect sizes (ESs). ES calculations were performed using robust variance estimation model with *R*-package.
Results: Study quality of the included studies was classified as fair (PEDro score = 4.58) with low to moderate certainty of evidence. Results showed no significant differences in ROM (ES = 0.01, $p = 0.88$), stiffness (ES = 0.09, $p = 0.67$), or passive peak torque (ES = −0.30, $p = 0.14$) between stretching or foam rolling and the other identified activities. Funnel plots revealed no publication bias.
Conclusion: Based on current literature, our results challenge the established view on stretching and foam rolling as a recommended component of warm-up programs. The lack of significant difference between interventions suggests there is no need to emphasize stretching or foam rolling to induce acute ROM, passive peak torque increases, or stiffness reductions.

Keywords: Range of motion; Passive properties; Muscle−tendon unit; Muscle tissue

1. Introduction

A vast number of studies have included different types of stretching to acutely enhance flexibility when preparing for subsequent training or competition.[1,2] However, a number of narrative reviews[3−7] and a systematic review[8] have illustrated that prolonged static stretching can induce subsequent muscle strength and power deficits. These findings highlighted the need for alternative protocols to acutely improve flexibility without adversely affecting performance. Therefore, foam rolling received greater attention over the past decade as researchers sought to enhance range of motion (ROM) without negatively affecting subsequent speed-strength parameters.

Numerous articles have investigated the acute effects of foam rolling on flexibility and force output as well as passive properties, using different degrees of roller hardness,[9] rolling velocities,[10] roller massagers,[11] and combinations of foam rolling with or without stretching and/or vibration.[12−14] They

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found meaningful ROM increases, which are considered comparable to those of stretching.[15,16]

Interestingly, as an additional benefit, unilateral stretching or rolling improved the contralateral limb ROM,[17–19] which is hypothesized to be attributable to neural drive mechanisms.[20] Moreover, some authors hypothesized that stretching or rolling a single leg would also affect the ROM in a remote part of the body (heterologous muscles).[18] Behm et al.[21] confirmed these effects, showing ROM increases in the upper body when intervening on the lower extremities, referring to the so-called global effects of stretching and foam rolling. These findings suggest that if unilateral activities have global effects then a muscle may not need to be stretched or rolled directly to attain flexibility improvements.

In general, observed acute ROM increases with stretching and foam rolling were attributed to reduced musculotendinous stiffness, thixotropic effects, or a myofascial release effect.[15,16] Even though research showed foam rolling and stretching to impact passive tissue stiffness and thixotropic effects as well as pain perception,[22,23] these effects are induced by different biological processes, such as improved synovial fluid extraction (reducing joint friction),[24] improved contractile properties by enhanced enzymatic activity, reduced stiffness, and improved viscosity.[25] However, these acute effects are not exclusive to foam rolling and stretching, as they are frequently described in response to enhanced muscle temperature (warm-up effects). Since warm-up effects are global in nature, affecting the contralateral as well as other remote body regions,[5,21] we speculate that ROM as well as stiffness changes could be meaningfully impacted by enhanced muscle and/or core temperature instead of by other specific effects. However, literature relating changes in temperature to ROM increases is scarce.

Nevertheless, there are studies suggesting that ROM increases accompanied by changes in passive properties are not exclusively attributable to stretching or foam rolling. For example, Morales-Artacho et al.[26] and Hubley et al.[27] showed that stretching and foam rolling can be substituted with cycling and jogging, respectively. Moreover, Warneke et al.[28] recently showed parallel increases in hip flexion ROM as well as non-rolled plantar flexors ROM when using 4 × 45 s of hamstrings foam rolling or sham-rolling. Finally, since Takeuchi et al.[29] and Oranchuk et al.[30] showed meaningful ROM increases just by using a hot water bath, we hypothesize that any activity that warms the muscle may enhance flexibility and, therefore, we reject the frequently postulated theory that attributes acute ROM increases primarily to foam rolling or stretching. To test this hypothesis, we performed a systematic literature search to find studies that compared stretching or foam rolling with other warm-up strategies to determine the acute effects on ROM and to explore whether or not there is a significant difference.

2. Methods

Prior to starting and considering ethical publishing standards,[31] we registered the study in the PROSPERO database (CRD42023439426). The review was performed adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for systematic review with meta-analysis.

2.1. Literature search

The systematic literature search was conducted by 3 independent authors (KW, EL, and GP) using "Patient/population Intervention Comparison Outcomes" guidelines and performed via MEDLINE/PubMed, Web of Science, and SPORTDiscus (inception to August 2023); the search was manually supplemented using Google Scholar. The following criteria were applied for study inclusion: (a) healthy participants of all ages; (b) comparison of stretching or foam rolling intervention with any other intervention; (c) investigation of at least 1 of the following parameters: ROM, muscle/tendon stiffness, or passive torque. Trials (a) comparing different types of stretching, (b) comparing different types of foam rolling, (c) not reporting ROM or passive property adaptations, and (d) not performing training (kinesio tape, acupuncture, *etc*.) were excluded.

While there is no debate on the definition of static stretching or different versions of proprioceptive neuromuscular facilitation stretching (including the contract relax, and the contract relax agonist contraction) or foam rolling,[32] authors do use a variety of terms to describe dynamic stretching, which complicated study inclusion. Behm[32] as well as Opplert and Babault[2] defined dynamic stretching as movement performed over the full ROM that would cause a large increase in heterogeneity; studies exploring acute full ROM strength training effects would be included, for example. To counteract this limitation, we agreed to exclusively include studies performing controlled, dynamic movements in the end ROM (back and forth movements). Referring to Behm and Chaouachi,[3] "dynamic" (controlled movements) and "ballistic" (less controlled and rapid movements) stretching effects were often pooled, therefore ballistic stretching was considered a subcategory of dynamic stretching in this review.[2]

Previous analyses compared the effects of different types of stretching with non-intervened control conditions[21] or foam rolling with non-intervened control conditions as well as stretching with foam rolling, showing that either is effective to increase ROM compared to no intervention; however, a direct comparison between stretching and foam rolling found no significant difference between them.[15] Thus, we excluded direct stretching *vs*. foam rolling comparisons from our calculation. Due to the aforementioned lack of differences in acute ROM effects between stretching and foam rolling interventions, we considered both to be equally effective and, thus, compared either against alternative interventions. Studies comparing the main intervention (either stretching or foam rolling) with the same intervention plus an additional stimulus (such as electromyostimulation or vibration rolling) were also excluded, since the basic intervention was considered the same. The search terms were created based on the requirements of each database. The literature search in PubMed was conducted using the following term:

(acute[Title/Abstract] OR immediate[Title/Abstract]) AND (flexib*[Title/Abstract] OR Stiffness[Title/Abstract] OR "passive torque"[Title/Abstract] OR "tissue compliance" [Title/Abstract] OR elasticity[Title/Abstract] OR "youngs modulus"[Title/Abstract] OR "resistive torque"[Title/Abstract] OR "passive properties"[Title/Abstract] OR "passive property"[Title/Abstract] OR "passive peak torque"[Title/Abstract] OR "peak resistive torque" [Title/Abstract] OR "range of motion" [Title/Abstract] OR ROM [Title/Abstract] OR "joint mobility"[Title/Abstract] OR warm-up[Title/Abstract] OR "warming up"[Title/Abstract] OR "warm up"[Title/Abstract]) NOT (patients[Title/Abstract] OR stroke[Title/Abstract] OR elderly[Title/Abstract] OR diseases[MeSH] OR aged[MeSH] OR palsy [Title/Abstract] OR sclerosis[Title/Abstract] OR Review [Publication Type] OR cogni*[Title/Abstract]).

Additionally, the reference lists of the included studies as well as related reviews were screened for further eligible articles.

2.2. Methodological study quality and risk of bias

Risk of bias assessment was performed by 2 independent investigators (LHL and DJ) using the PEDro scale.[33,34] Scoring was performed by 2 independent investigators (LHL and DJ). If they did not reach consensus, a 3rd examiner (GP) provided the decisive vote. The risk of publication bias was quantified by the Egger's regression test in addition to a visual inspection of modified funnel plots with the extension for dependent effect sizes (ESs)[35] to account for multiple study outcomes.

Certainty of evidence was rated according to the GRADE working group criteria,[36] which utilizes the following categorizations: "very low" (effect estimate very uncertain), "low" (further research is very likely to change the effect estimate), "moderate" (further research is likely to change the effect estimate), or "high" (further research is very unlikely to change the effect estimate). Following the rating criteria and the inclusion of (randomized) controlled trials, the quality of evidence was initially classified as high and adjusted afterwards. Downgrades were made based on possible study limitations, such as risk of bias, inconsistency, uncertainty of directness, imprecise data, and reporting bias; upgrades were made based on strong evidence of association, evidence of a dose−response gradient, and plausible confounders.

2.3. Data processing and statistics

Data were extracted by KW, DJ, and EL and double-checked by GP. If no original values (mean and SD) were provided in the full text, authors were contacted, and data were requested. If no answers were received, we read mean and SD from graphics, if applicable. Otherwise, the study was excluded from further calculation. Using collected mean and SD from pre- and post-tests, changes from pre- to post-test were calculated by applying the following formula:

$$\text{Mean}_{(\text{post-test})} - \text{Mean}_{(\text{pre-test})}.$$

SDs were pooled as follows:

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

To account for dependency of ES in a meta-analysis with multiple outcomes, we performed robust variance estimation to pool the standardized mean differences (SMDs) and 95% confidence intervals (95%CIs) between stretching and comparison as well as between foam rolling and comparison with regard to ROM and passive properties. To account for minimal heterogeneity in the study outcome (τ^2) and methods, subgroup analyses were performed for the effects of stretching in general, static stretching, dynamic stretching, and foam rolling on ROM, as well as for the effects of stretching and foam rolling on tissue passive properties. Pooled ES were interpreted as follows: trivial: $0 \le \text{ES} < 0.2$; small: $0.2 \le \text{ES} < 0.5$; moderate: $0.5 \le \text{ES} < 0.8$; and large: $\text{ES} \ge 0.8$.[37] All calculations were performed using *R* and the robumeta package[38] considering study design (parallel and cross-over design).

3. Results

3.1. Search results and study characteristics

The results of the literature search are illustrated in Fig. 1, with a total of 38 studies[26,27,30,39−73] ($n = 1134$ participants, male = 567, female = 415, and 4 studies including 152 participants without information regarding sex;[27,39−41] ES: $n = 140$) meeting the inclusion criteria. Of these, 25 papers compared the effects of stretching to those of alternative activities on ROM;[27,39−43,45,46,48,49,51,54,55,57−63,65,66,70,71,73] 23 studies used static stretching,[27,39−43,45,46,48,49,51,55,57−63,65,66,70,71] while 5 studies included dynamic or proprioceptive neuromuscular facilitation stretching variants.[49,54,58,62,63] Additionally, 11 studies compared the effects of foam rolling with those of an alternative activity on ROM.[26,30,49−51,53,56,58,64,68,69] We included 4 studies (ES: $n = 23$)[44,46,47,72] investigating the effects of stretching and 3 studies (ES: $n = 7$) addressing the effects of foam rolling on stiffness,[26,53,67] while 3 studies (ES: $n = 12$) addressed the effects on passive peak torque.[46,47,53] The majority ($n = 37$) of the articles addressed muscles of the lower extremities,[26,27,30,39−70,72,73] while only a single intervention targeted muscles of the upper body.[71] Studies matching the inclusion criteria compared stretching and foam rolling with different types of alternative activities, including walking,[26,69] vibration,[56,57,59,60,70] cycling,[26,27,55,67] calisthenics,[40] strength training,[44,47,64,72,73] electrical stimulation,[73] heat package passive warm up,[30] and cryotherapy.[59] Stretching durations performed in the included acute studies ranged from 10 s[57,63] to 60 min[39] of static stretching per set, with 1 set[39] to 8 sets.[62] With the included foam rolling studies, set duration ranged from 20 s[69] to 15 min (each set lasting 1 min of unilateral or bilateral rolling),[26] with 1 set[51] to 8 sets.[50] More

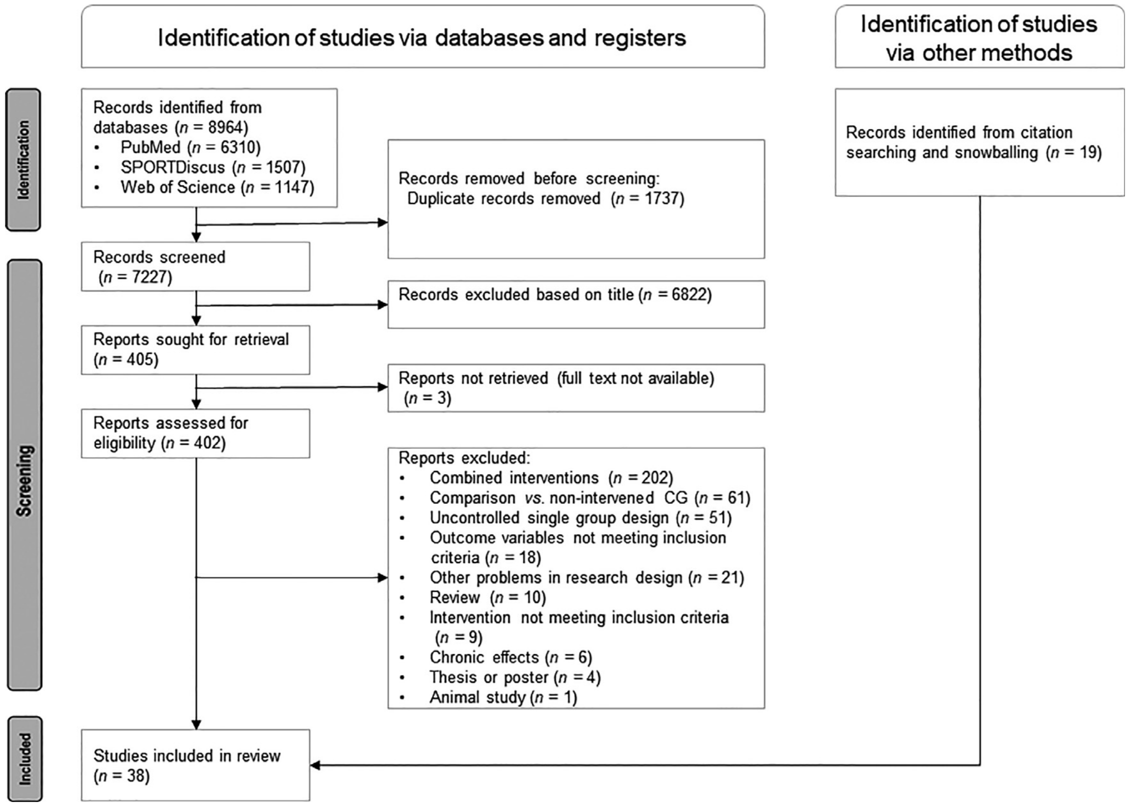

Fig. 1. PRISMA flow chart to illustrate literature search for stretching effects on passive properties. CG = control group; PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

detailed information is provided in Supplementary Table 1. Some special features should be considered when interpreting the results. A number of studies incorporated active warm-up activities such as cycling prior to stretching both before the intervention and after the pre-test.[42,48,66] Aune et al.[64] did a standardized warm-up before the intervention consisting of 5-min cycle ergometry (80 watts, 75−85 revolutions per minute), walking lunges (2 sets × 5 repetitions each leg), deep squats (2 sets × 5 repetitions), and supine glute bridges (2 sets × 5 repetitions). Cronin et al.[60] and Deguzman et al.[68] performed 5 min of jogging as a warm up prior to the testing. Furthermore, in some studies the authors stated that dynamic stretching was performed; however, since they used arm rotation, hip rotation, or other types of general dynamic warm-up routines,[42,48,49,52] we included those as alternatives to stretching and foam rolling.

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

The PEDro score rating showed a risk of bias rated as fair, with a score (mean ± SD) of 4.62 ± 1.26 (range: 3−8 points). Almost all studies (34 out of 38) used random group allocation, reported statistical between-group comparisons (38 out of 38), and provided both point measures and measures of variability (37 out of 38). While blinding of the participants and therapists was never achieved, investigator-blinding was accomplished in 10 studies.[30,41,43,45,48,54,61,62,71,73] Only 3 studies concealed the allocation[45,54,58] and adhered to the application of the intention-to-treat principle,[45,54,73] respectively. In 6 studies,[26,27,42,46,56,58] the groups were not considered similar at baseline with respect to the most important prognostic factors. Also, only about half of all studies reported the number of subjects in both pre- and post-testing or collected data from at least 85% of the participants included during post-testing (Supplementary Table 2). Applying the GRADE criteria, certainty of evidence for the comparison of the effects of stretching or foam rolling *vs.* those of alternative interventions on ROM was initially rated as high due to the inclusion of (randomized) controlled trials. The level of evidence was downgraded for risk of bias (1 point, i.e., PEDro score was fair). All other criteria did not lead to either down- or upgrading, so the overall level of evidence was considered moderate. The same applies for stretching and foam rolling *vs.* alternative subgroups regarding ROM changes. The quality of evidence for all stiffness and passive peak torque comparisons was downgraded further due to inconsistency (1 point, i.e., wide variation estimates across studies) and imprecision (1 point, i.e., small sample size and wide 95%CI showing high magnitude effect in both directions) of data. The level of evidence should thus be considered very low.

3.3. *Quantitative analysis of effects comparing stretching and foam rolling with alternative interventions*

When considering all types of stretching and foam rolling, no significant difference in ES was detected for ROM (ES = 0.05, 95%CI: −0.10 to 0.20, $p = 0.51$, $\tau^2 = 0.95$; 34 studies, ES: $n = 80$) compared to alternative interventions. None of our subgroup analyses (Table 1) showed a significant effect on ROM (ES: −0.27 to 0.065; 95%CI: −0.93 to 0.61; p: 0.31−0.91, τ^2: 0.06−0.56). Fig. 2 shows the forest plot comparing foam rolling with alternative interventions. Likewise, for passive properties, including stiffness and passive peak torque, no significant difference between stretching/foam rolling and any alternative intervention was reported (ES: −0.13 to 0.59; 95%CI: −2.39 to 3.57; p: 0.07−0.95, τ^2: 0.0−1.39) (Table 1).

Some authors[42,48,66] increased the heterogeneity in their testing procedure by including, for example, jogging after the pre-test. However, excluding these studies from the statistical calculation did not change the effects. We still did not find a significant difference in the measured changes (p: 0.58−0.99).

The absence of a publication bias was ensured by visual inspection of funnel plots (Fig. 3) and by performing Egger's regression tests. No publication bias was detectable for ROM or passive properties, including both foam rolling and stretching ($p = 0.32$), nor for subgroup assessment (stretching ROM: $p = 0.47$; foam rolling ROM: $p = 0.23$; stretching stiffness: $p = 0.23$; static stretching stiffness: $p = 0.45$; foam rolling stiffness: $p = 0.61$; passive torque: $p = 0.58$; and stretching passive torque: $p = 0.27$). Note that for subgroup analysis, including acute static stretching effects on ROM ($p = 0.04$), there was a significant publication bias without confirmation by visual inspection of the funnel plot (Fig. 3B).

4. Discussion

Our systematic review with meta-analysis was conducted to explore the necessity of using stretching or foam rolling, specifically, to induce acute ROM increases, as these practices have been commonly thought to induce positive adaptations such as ROM and passive peak torque enhancements as well as to decrease stiffness. Previous reviews did not show any difference in ROM increases when comparing stretching and foam rolling,[14−16] indicating that they have similar effects and underlying mechanisms.[15] Those effects, which are often described as specific to foam rolling and stretching, are also well-known effects of general warm-up routines. Therefore, we hypothesized that other interventions known to trigger similar mechanisms (e.g., enhanced muscle temperatures) would also provide sufficient stimulus to induce the listed adaptations. Accordingly, our meta-analysis included a total of 38 studies ($n = 1134$) comparing stretching and foam rolling with other interventions (walking, vibration, cycling, calisthenics, strength training, electrical stimulation, heat package passive warm up, and cryotherapy). Ultimately, we were not able to detect a significant difference for any of the included parameters. ROM values showed a moderate certainty of evidence, and stiffness and passive peak torque scores were rated as very low certainty of evidence. We found no significant differences in acute ROM in the 25 studies[27,39−43,45,46,48,49,51,54,55,57−63,65,66,70,71,73] that performed stretching or the 11 studies that used foam rolling,[26,30,49,50,51,53,56,58,64,68,69] each of which compared the effects of the activity of interest to those of other interventions. Considering that 7 studies[26,44,46,47,53,67,72] investigating acute changes in stiffness and 3 studies looking at acute passive torque also showed no significant difference,[46,47,53] we are led to question the necessity of stretching and foam rolling when aiming to acutely enhance ROM and passive peak torque or to decrease stiffness.

4.1. *Warm up and its impact on muscle performance and flexibility*

Our initial hypothesis was derived from basic scientific theories since we assume the simplest explanation to be the most likely (Ockham's razor). As a baseline rationale, we assume muscle contractions to be present in any kind of exercise or movement. Accordingly, since adenosine triphosphate (ATP) hydrolysis (splitting of ATP to ADP + Pi) results in energy release, this biochemical reaction is exothermic and,

Table 1
Meta-analytic results for chronic effects of stretching on passive properties providing effect size, 95%CI, significance, and heterogeneity.

Comparison	Effect size (95%CI)	p	Heterogeneity	Number of clusters/outcomes
Stretching/foam rolling *vs.* alternative	0.05 (−0.10 to 0.20)	0.51	0.95	34/80
Stretching *vs.* alternative on ROM	0.065 (−0.060 to 0.200)	0.31	0.27	25/58
Static stretching *vs.* alternative on ROM	−0.03 (−0.20 to 0.14)	0.72	0.06	23/51
Dynamic/PNF stretching *vs.* alternative on ROM	−0.03 (−0.67 to 0.61)	0.91	0.10	5/7
Foam rolling *vs.* alternative on ROM	−0.27 (−0.93 to 0.40)	0.39	0.56	11/16
Stretching/foam rolling *vs.* alternative on stiffness	0.09 (−0.21 to 0.40)	0.49	0.10	7/33
Stretching *vs.* alternative on stiffness	−0.05 (−0.42 to 0.30)	0.65	0.0	4/26
Foam rolling *vs.* alternative on stiffness	0.59 (−2.39 to 3.57)	0.48	1.39	3/7
Stretching/foam rolling *vs.* alternative on passive peak torque	−0.13 (−0.28 to 0.02)	0.07	0.0	3/12

Notes: Stretching/foam rolling refers to both interventions, while subgroup analyses were performed for stretching, static and dynamic stretching respectively and foam rolling on ROM, as well as for stretching and foam rolling on stiffness. Because of lacking effect sizes, we were not able to perform subgroup analysis for passive torque comparisons.
Abbreviations: 95%CI = 95% confidence interval; PNF = proprioceptive neuromuscular facilitation; ROM = range of motion.

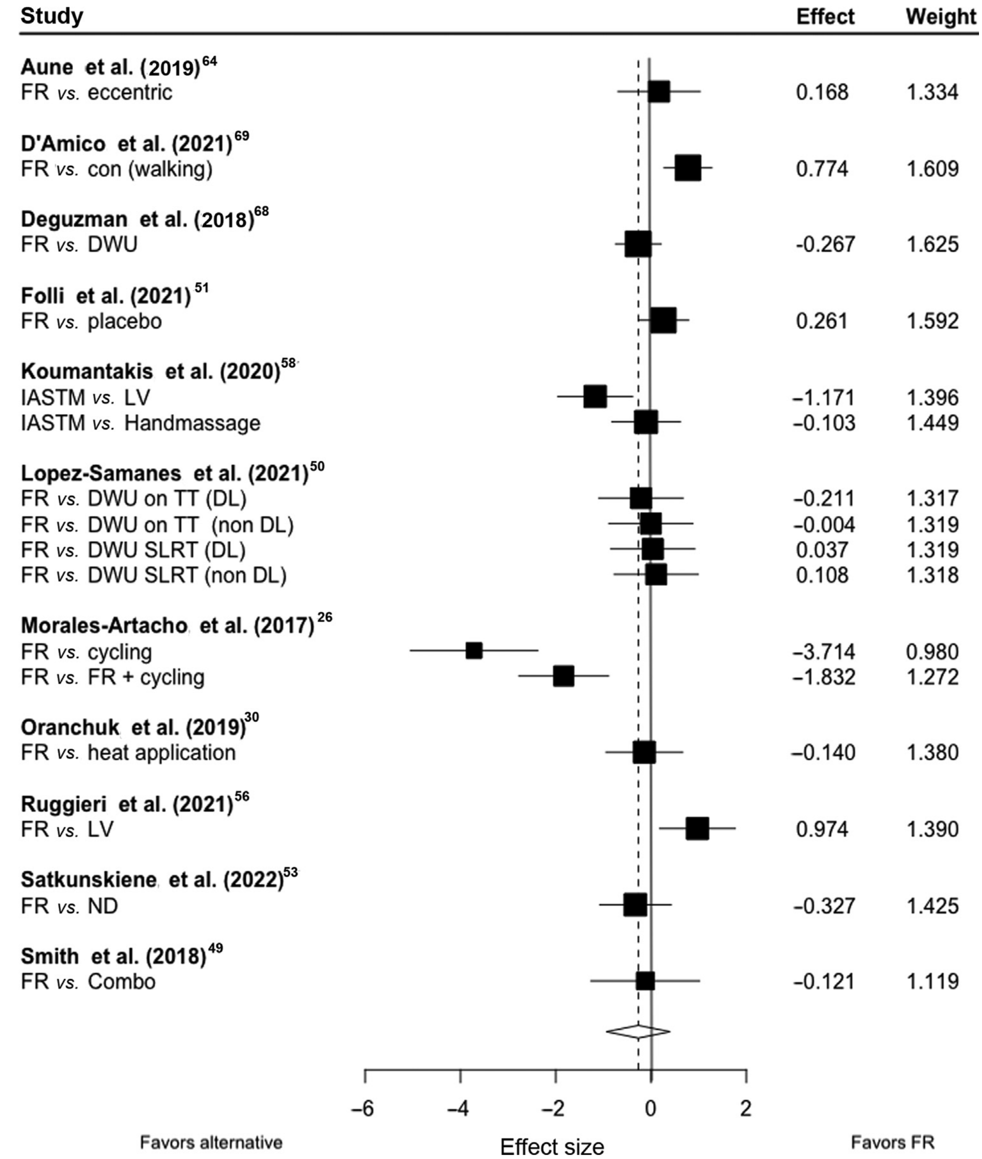

Fig 2. Forest plot showing comparisons between the effects of applied pressure induced by FR and roller massage and those of any alternative intervention on ROM, showing no significant difference between interventions (ES = −0.374, 95%CI: −1.150 to 0.400, $p = 0.031$). 95%CI = 95% confidence interval; con = control; DL = dominant leg; DWU = dynamic warm up; FR = foam rolling; IASTM = instrument-assisted soft tissue mobilization; LV = local vibration; ND = nerve directed gliding; non DL = non-dominant leg; ROM = range of motion; SLRT = straight leg raise test; TT = Thomas test.

thus, increases temperature in the tissue. Heating effects and their related positive influence on muscle contractile properties[74−78] and tissue visco-elasticity[24,25] is not a novel suggestion. Interestingly, no exercise or movement is required to induce performance improvements: recent studies provide evidence of the beneficial effects of using passive heating alone, for example, via hot water baths.[79,80] While these studies focused on performance parameters, further effects such as increased intramuscular fluid,[81,82] improved synovial fluid inflow leading to reduced joint friction,[24] and improved viscoelastic properties[25] were reported.

In addition to meaningful temperature increases of up to 2.4 ˚C as a result of hot water bathing,[79,80] some studies pointed out similar muscle warming effects in response to self-myofascial release interventions[83] as well as stretching of the hamstrings,[84] indicating that both of these interventions could be sufficient to induce the abovementioned thermal adaptations, thereby contributing to enhanced ROM. As hypothesized, comparable effects were reported by performing active training. Krzysztofik et al.[85] reported decreases in Achilles tendon stiffness and quadriceps stiffness, accompanied by an increase in skin temperature, in response to performing 3 different squatting protocols. Instead of specifically attributing these effects to the action of squatting alone, they were explained, at least in part, by the biological processes attributed to warm up (i.e., increased muscle temperatures). It is noteworthy that, when performing stretching and foam rolling, acute ROM increases were mostly attributed to specific foam-rolling and stretching effects, such as thixotropic effects, stiffness reductions, or stretching pain threshold changes.[15,86]

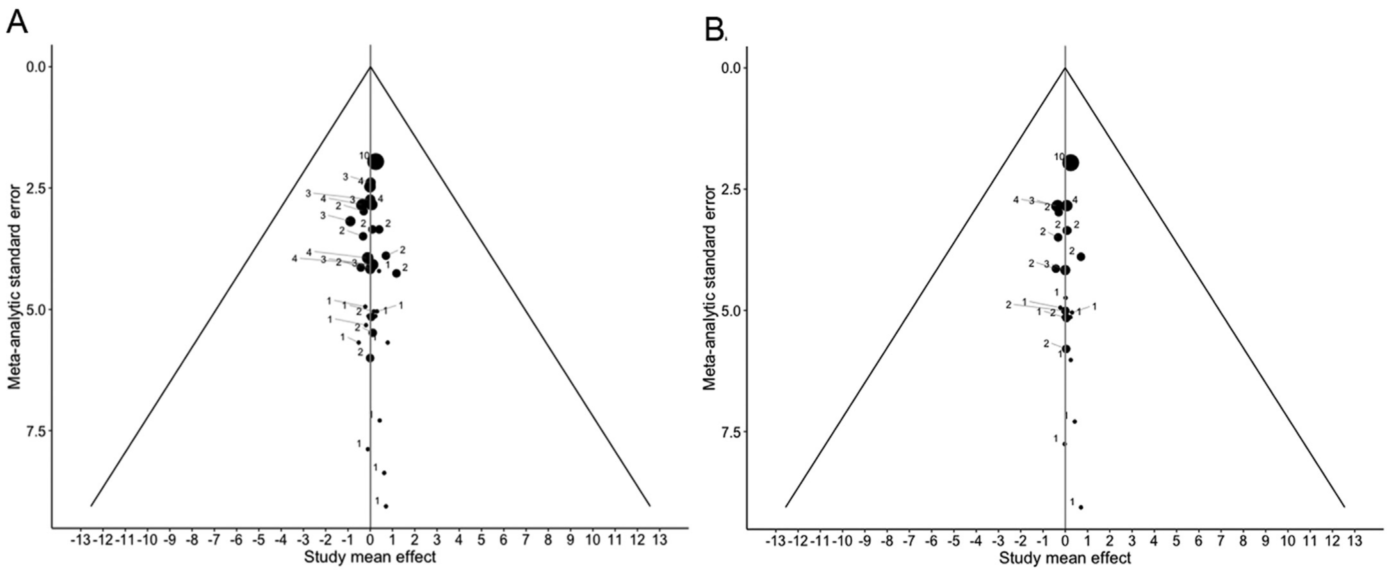

Fig. 3. (A) There is no publication bias according to the Egger's test and no significant difference between all types of stretching and comparison interventions. (B) The publication bias of static stretching compared with alternatives, as suggested by the Egger's test. Numbers and size of the dots represents the number of included study outcomes.

However, these effects were also reported in many alternative interventions (Supplementary Table 3). As early as 1984, Hubley and colleagues[27] compared the effects of 15 min of either cycling or stretching, finding that they resulted in similar ROM increases. Cronin et al.[60] compared the acute effects of stimulating the hamstrings via vibration with those of static stretching and showed that both interventions were similarly effective at inducing ROM increases. Atha et al.[87] compared the effects of vibration with those of electrical stimulation, showing no significant difference between groups, while Warneke et al.[39] were not able to find any significant difference in acute ROM increases using 5 × 12 repetitions of full ROM calf raises or 1 h of static calf stretching. These are just a few examples of investigations that raise questions about the relevance of using stretching or foam rolling, specifically, when aiming to acutely improve ROM. As we found, several other interventions achieved the same goal, including cycling[26,88] and hot water baths,[29,88] eccentric stiff-leg deadlifts,[89,90] whole body vibration,[91] cryotherapy,[92,93] different massage techniques,[94] electromyostimulation,[95,96] and Tecar therapy,[97] as well as yoga (alone[98] or combined with heat[99]). In some studies, effects of alternative interventions provided greater ROM than those induced by stretching or foam rolling. For example, Morales-Artacho et al.[26] showed significantly higher ROM improvements with cycling *vs.* foam rolling.

4.2. Further approaches to explaining acute ROM increases

There are several explanatory approaches for interpreting the effects of acute stretching/foam rolling. In contrast to the previously preferred rationale for discussing contralateral stretching or foam rolling effects,[18,100,101] which attributed these mostly to learning effects, pain threshold changes, or afferences (e.g., pain, reflex, pressure, muscle length changes),[17,18,101] these effects can also be explained in terms of muscle activity-induced warm-up effects, which are global and would therefore affect the remote muscle groups.

Furthermore, when a state of enhanced physical activity (independent of stretching, foam rolling, jogging, cycling, *etc.*) comes to an end, muscle temperature is assumed to drop. Coincidentally, several studies reported decreasing flexibility within this time window.[49,71]

A controversial theory suggests changes in neuronal aspects influencing the electromyography muscle activity. However, Magnusson and colleagues[102] studied acute stretching effects on passive peak torque and muscle activity in healthy and spinal cord injured (with complete motor loss) subjects; they found no significant difference in the change of these parameters between groups and, consequently, hypothesized that pain tolerance and a change in viscoelastic behavior were driving factors in passive peak torque improvements.[102,103] Another potential mechanism of action is the stretch-induced inhibition of afferent signals to the motoneuron pool accompanied by a reduction in reflex excitability (Hoffman reflex) due to desensitization of the muscle spindle.[104] In this regard, in manual medical studies, changes in the central nervous system due to manipulation or mobilization techniques[105,106] were speculated to be an underlying mechanism that could alter pain perception. However, this outcome (reduced pain perception) was also observed following physical activity in general.[107,108] An additional factor that could affect the explored outcomes is the stimulation of the autonomic nervous system by application of pressure or vibration on the tissue that regulates the perception of pain, skin temperature, and conductance;[109] and it is possible that the sympathetic nervous system could affect smooth muscle cells in the muscle and fascial tissue.[110] Nevertheless, mechanosensory-induced changes in sympathetic tone could., at least theoretically, contribute to a relaxation of the tissue, thus changing the blood flow and increasing tissue temperature and ROM.[111]

Finally, to clarify, we do not rule out any specific effects induced by either stretching or foam rolling, but we wish to emphasize the commonalities of ROM-inducing mechanisms that can be attributed to not only stretching and foam rolling but many other warm-up activities as well. The most obvious explanatory approach[112] should be falsified[113] before speculating about (highly) specific and probably unlikely alternative explanations. This falsification, to the best of our knowledge, has not been done. There was no literature showing that listed adaptations are *not* attributable to simple warm-up effects.

4.3. Limitations

One of the most prominent criticisms of meta-analyses is the non-comparability of interventions and study outcomes considered in the calculation of overall ES.[114] Meta-analytic calculations work with outcome data, considering inputted values for the analysis, heterogeneity arises from comparing different outcomes. To reduce heterogeneity in the interventions, we included homogeneous outcomes (ROM and passive properties) separately by performing subgroup analyses for both primary procedures, foam rolling and stretching. Since calculation programs do not distinguish between the origin of the values (e.g., passive control or comparison group) and only compare the resulting pooled ES, this approach seems a valid one to check for significant differences between 2 intervention routines. Accordingly, previous analyses have compared 2 interventions to figure out which is more effective.[14,15] Even though no asymmetry in funnel plots was detected when assessing risk of publication bias, we cannot rule out a bias in the results caused by including several parameters in the comparison group, which should be considered when interpreting the results.

We acknowledge further limitations of the study related to group inclusion and exclusion. We agreed to include studies using common stretching interventions, such as dynamic, ballistic, or static conditions, as well as proprioceptive neuromuscular facilitation. However, as we acknowledge in the Methods section, these interventions can be defined differently, especially in the case of dynamic stretching. A unique definition of dynamic stretching is warranted.

Discrepancies in other studies should also be noted. For example, Nelson[65] compared the effects of eccentric contraction to those of static stretching; however, eccentric contractions could also be defined as dynamic stretching. Therefore, we carefully checked the terminology as well as the performed intervention, which led us to include studies that described the comparison of static and dynamic stretching; however, Nelson[65] used a more active mobility routine, which was described as dynamic stretching. Additionally, a (systematic) distortion stems from the implementation of warm ups (such as cycling, walking lunges, deep squats) prior to the warm-up routines tested and compared with one another.[42,46,48,49,52,60] To counteract this limitation and account for additional evidence, we added the table with the non-systematic search to our discussion.

Last, considering the GRADE criteria, the certainty of evidence differs highly between parameters. We had to subtract grades due to risk of bias, imprecision, and inconsistency for stiffness and peak torque outcomes. These limitations of the literature probably arise from a small number of studies (and ES) with inconsistency in the results, leading to broad confidence intervals in the analysis. Accordingly, the results for foam rolling effects on, for example, stiffness show ES = 0.59 (95%CI: −2.39 to 5.57); however, they did not reach the level of significance ($p = 0.42$). This result is, in fact, not interpretable. However, due to the small number of included studies, performing sub-group analyses was not possible.

4.4. Practical applications

The present study showed no significant difference between stretching or foam rolling and any other intervention with regard to acute effects on ROM or passive properties. Based on current literature, we cannot rule out the possibility that there are specific effects of both types of interventions. However, for coaches or therapists who are aiming to acutely increase flexibility or decrease stiffness, it seems there is no need to specifically or exclusively perform foam rolling or stretching. More aspects than ROM must be taken into account because preparation for subsequent performance is a multifactorial paradigm.[115] Consequently, reaching the same flexibility goals with any alternative intervention challenges the established view on stretching and foam rolling; and, especially when the importance of time economics is taken into consideration, time-saving general warm-up routines (e.g., dynamic exercises[116,117] or cycling[26,88]) may be preferred in practice.

To clarify, we are not suggesting exclusion of stretching or foam rolling from training routines, especially since we did not perform analyses regarding acute or chronic effects on back pain or other benefits, such as decreased incidence of musculotendinous injuries with change of direction or explosive movements.[118,119] Nevertheless, practitioners may not be interested in the molecular differences between training interventions if their goal is an immediate improvement in flexibility. While the effects of interest could be attributable to warm ups, literature is scarce regarding this theory.

5. Conclusion

Current evidence shows that stretching and foam rolling can improve ROM in isolation, but it does not rule out that acute flexibility effects measured after foam rolling or stretching could also be attributed to the effects of general warm-up activities. Based on the present analysis, it seems that stretching and foam rolling do not provide additive effects for ROM when combined with other warm-up activities. Therefore, it is hypothesized that any activity that increases core and muscle temperatures, such as stretching, foam rolling, or other warm-up activities, may be used interchangeably or in combination to acutely increase ROM or affect passive properties.

6. Outlook

Referring specifically to foam rolling and stretching, it is beneficial to contrast their effects with the effects of other interventions. Since our outcomes revealed no significant differences between any intervention and stretching or foam rolling, further studies will be required to investigate the effects of underlying mechanisms to discover physiological differences. While the literature provides extensive information on ROM changes with stretching and foam rolling, there is a continued need to investigate the physiological aspects or mechanisms of foam rolling[11,120] and stretching along with other warm-up activities. To exclude the effects of general warm-ups, researchers should compare the effects of other types of activity, such as jogging, cycling, *etc*., with those of stretching or foam rolling.

Authors' contributions

KW developed the idea of the analysis, performed the data extraction, calculated the statistics, wrote the manuscript, and revised the study; GP was included to the data extraction, quality assessment, and graphical illustration; LHL assisted in data extraction and performed the quality assessment; DJ was included to the data extraction and quality assessment; EL was included to the data extraction and revisions of the manuscript; SDS was involved in the writing of the discussion and included his expertise to the revisions of the manuscript; AZ commented on the manuscript and included her expertise in the field; DGB performed the language check, reviewed the literature, included his expertise, and supervised the project. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Data availability

Original data can be provided upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

Supplementary materials

Supplementary materials associated with this article can be found in the online version at doi:10.1016/j.jshs.2024.01.006.

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