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Review

Chronic effects of stretching on range of motion with consideration of potential moderating variables: A systematic review with meta-analysis

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Abstract

Background: It is well known that stretch training can induce prolonged increases in joint range of motion (ROM). However, to date more information is needed regarding which training variables might have greater influence on improvements in flexibility. Thus, the purpose of this meta-analysis was to investigate the effects of stretch training on ROM in healthy participants by considering potential moderating variables, such as stretching technique, intensity, duration, frequency, and muscles stretched, as well as sex-specific, age-specific, and/or trained state-specific adaptations to stretch training.

Methods: We searched through PubMed, Scopus, Web of Science, and SportDiscus to find eligible studies and, finally, assessed the results from 77 studies and 186 effect sizes by applying a random-effect meta-analysis. Moreover, by applying a mixed-effect model, we performed the respective subgroup analyses. To find potential relationships between stretch duration or age and effect sizes, we performed a meta-regression.

Results: We found a significant overall effect, indicating that stretch training can increase ROM with a moderate effect compared to the controls (effect size = −1.002; $Z = -12.074$; 95% confidence interval: −1.165 to −0.840; $p < 0.001$; $I^2 = 74.97$). Subgroup analysis showed a significant difference between the stretching techniques ($p = 0.01$) indicating that proprioceptive neuromuscular facilitation and static stretching produced greater ROM than did ballistic/dynamic stretching. Moreover, there was a significant effect between the sexes ($p = 0.04$), indicating that females showed higher gains in ROM compared to males. However, further moderating analysis showed no significant relation or difference.

Conclusion: When the goal is to maximize ROM in the long term, proprioceptive neuromuscular facilitation or static stretching, rather than ballistic/dynamic stretching, should be applied. Something to consider in future research as well as sports practice is that neither volume, intensity, nor frequency of stretching were found to play a significant role in ROM yields.

Keywords: Flexibility; Long-term stretching; Stretch training

1. Introduction

The most common stretching techniques are static, ballistic, dynamic, and proprioceptive neuromuscular facilitation (PNF) stretching.[1−7] All of these methods are able to increase joint range of motion (ROM) when implemented consistently in a training program.[8−11] Traditionally, the most commonly used technique is static stretching,[12−16] where the joint is held at the maximum ROM at a specific stretch intensity (e.g., until the point of discomfort).[17] However, in response to research over the last 25 years reporting performance decrements following prolonged static stretching, there has been a shift toward emphasizing dynamic and ballistic stretching, especially in athletic populations.[3,6,18] Dynamic stretching involves moving the joint repeatedly at a controlled velocity throughout the whole ROM.[11] A ballistic stretch is a form of dynamic stretching, but performed at higher velocities where the joint may reach the maximum ROM.[10] Additionally, PNF stretching is a technique frequently used in sports practice as well as in

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rehabilitation. The PNF technique can be divided into various sub-techniques. In the passive techniques ("contract−relax" or "hold−relax"), the target muscle is placed into a position of stretch followed by a static contraction. The muscle is then passively moved into a greater position of stretch. In the active technique ("contract−relax−antagonist−contract"), the final passive stretch is exchanged by an active contraction of the antagonist, which stretches the target muscle.[4] Due to the different stimuli applied in the various stretching techniques, it is expected that changes in ROM due to long-term stretch training can be explained by different adaptations within the muscle−tendon unit[13,19,20] and/or by changes in stretch or pain perception.[8,13] However, to date it is not clear which stretching technique will result in the highest ROM gains over the long term.

Besides stretching technique, stretch intensity may be another important factor underlying the extent of gains in ROM. In general, stretch intensity can be divided into: (a) below point of discomfort (i.e., low-intensity stretching) and (b) until or at the point of discomfort (i.e., high-intensity stretching).[17] Although it was reported that a single (acute) bout of high-intensity stretching exercise is more favorable compared to low-intensity stretching with regard to ROM gains,[21,22] this is not clear yet for training (i.e., long-term, chronic) studies. While 1 study reported higher gains with a more intense stretching approach compared to low-intensity stretch training,[17] others showed no such differences.[21,23] Thus, it would be important to perform a meta-analytic analysis to point out whether painful, uncomfortable, or rather unpleasant stretching sensations are required to get the highest chronic gains in joint ROM.

In addition to stretching technique and intensity, sex-specific adaptations resulting from stretch training might be relevant. Since most existing studies with sport science-related research questions are biased towards male participants,[24] it will be important to collect evidence from both sexes. Although it is well understood that muscle function and structure differ between males and females,[7,25] it is not yet well understood whether sex-specific adaptations exist as a result of stretch training.

It is well known that stretch training can increase ROM in both sedentary and athletic populations.[26] However, it is not yet well understood whether such increases are pronounced in any of these groups more than others. Additionally, less data is available on muscle-specific or age-specific responses. Thus, it will be important to summarize all existing evidence and to calculate and compare the respective effect sizes (ESs).

Therefore, the purpose of this meta-analysis was to investigate the effects of stretch training (≥2 weeks) on joint ROM in healthy participants. Furthermore, we aimed to investigate the influence of potential moderating factors, such as stretching technique, intensity, duration, frequency, and muscles stretched, as well as sex-specific, age-specific, and/or trained state-specific adaptations to >2 weeks of stretch training.

2. Methods

This review was conducted according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses guidelines and the suggestions for systematic reviews with meta-analysis from Moher et al.[27]

2.1. Search strategy

An electronic literature search was performed in PubMed, Scopus, Web of Science, and SportDiscus. Papers published through September 2022 were considered for inclusion. Using AND and OR Boolean operators, a systematic search was conducted using the following keywords: flexibility, "range of motion", extensibility, and stretch*. In addition to the aforementioned keywords, the studies were filtered using the subsequent keywords to include controlled trials: "randomized controlled trial", "controlled clinical trial", "randomized", "placebo", "randomly", and "trial". Furthermore, to exclude animal studies we added a NOT operator with the following MeSH Term "exp animals/not humans". For example, the following search query was used in PubMed: (((("flexibility"(Title/Abstract)) OR ("range of motion"(Title/Abstract))) OR ("extensibility"(Title/Abstract))) AND ("stretch*"(Title/Abstract))) AND (((((((("randomized controlled trial"(Publication Type)) OR ("controlled clinical trial"(Publication Type))) OR ("randomized"(Title/Abstract))) OR ("placebo"(Title/Abstract))) OR ("clinical trials as topic"(MeSH Terms))) OR ("randomly"(Title/Abstract))) OR ("trial"(Title/Abstract))) NOT (exp animals/not humans(MeSH Terms))). The systematic search was conducted by 8 independent researchers (SA, SHA, AD, AZ, RG, CE, CS, and AG). Initially, articles were screened by title and abstract. If the content remained unclear, the full text was retrieved for further screening, and relevant papers were identified. Following this screening process, the independent researchers compared their findings. Disagreements were resolved by jointly reassessing the studies against the eligibility criteria.

2.2. Inclusion and exclusion criteria

This review considered studies that investigated the training effects of stretching on joint ROM in healthy participants. The studies were included when they were either randomized controlled trials or controlled trials with an intervention duration ≥2 weeks.[28] This means that we excluded studies dealing with the acute effects of stretching (or interventions shorter than 2 weeks), those that investigated any combined treatment (e.g., stretching and strength training), and those that had another treatment as the control condition (e.g., foam roller). Moreover, we excluded review papers, case reports, special communications, letters to the editor, invited commentaries, conference papers, and theses.

2.3. Extraction of the data

We extracted the following data from included papers: the characteristics of the participants (i.e., age, trained state, sex), the sample size, the characteristics of the intervention (i.e., stretch per bout, stretch duration per week, stretch frequency per week, stretch technique, stretch intensity, muscle stretched, muscle tested, supervision of the stretch intervention), and the results of the main variables (flexibility parameters). For the flexibility parameters, pre- and post-intervention values plus SDs of the foam rolling and control groups were extracted. If some of the required data were missing from the included studies, the authors of the studies were contacted via email or similar channels (e.g., ResearchGate).

2.4. Statistics and data synthesis

The meta-analysis was performed using Comprehensive Meta-Analysis software (Biostat, Englewood, NJ, USA) according to the recommendations of Borenstein et al.[29] By applying a random-effect meta-analysis, we assessed the ES in terms of the standardized mean difference. If any study reported >1 ES, the mean of all the outcomes (ES) within the single study was used for the analysis and was defined as combined (as suggested by Borenstein et al.[29]). Moreover, we performed subgroup analyses by applying a mixed-effect model. Although there is no general rule of thumb,[29] we only performed subgroup analyses when there were ≥3 studies included in the respective subgroups. Consequently, we performed subgroup analyses for the muscles tested (sit and reach *vs*. isolated hamstrings *vs*. quadriceps *vs*. triceps surae *vs*. hip flexors *vs*. shoulder), intensity of stretch (high intensity *vs*. low intensity), trained state of the participants (recreational active *vs*. professional athletes *vs*. sedentary), stretching techniques (static *vs*. dynamic/ballistic *vs*. PNF), supervision of the stretching intervention (fully supervised *vs*. periodically supervised *vs*. non supervised), and sex (male *vs*. female). To determine differences between the ESs of the subgroups, Q-statistics were applied.[29] Moreover, we conducted a meta-regression to assess possible relationships between the moderating variables (i.e., age of the participants, total stretch duration, stretch frequency per week). If the moderating variables could not be clearly defined within a single study (e.g., mixed sex), the study was not considered for the moderating analyses. According to the recommendations of Hopkins et al.,[30] the effects for a standardized mean difference of <0.2, 0.2−0.6, >0.6−1.2, >1.2−2.0, >2.0−4.0, and >4.0 were defined as trivial, small, moderate, large, very large, and extremely large, respectively. I^2 statistics were calculated to assess the heterogeneity among included studies, and thresholds of 25%, 50%, and 75% were defined as having a low, moderate, and high level of heterogeneity, respectively.[31,32] An α level of 0.05 was defined for the statistical significance of all the tests.

2.5. Risk of bias assessment and methodological quality

The methodological quality of the included studies was assessed using the PEDro scale. In total, 11 methodological criteria were rated by 8 independent researchers (SA, SHA, AD, AZ, RG, CE, CS, and AG), and each of the methodological criteria was assigned either 1 point or no points. Higher scores indicated better methodological quality. In the case of conflict between researchers, the methodological criteria were reassessed and discussed. Moreover, statistics from the Egger's regression intercept test and visual inspection of the funnel plot were applied to detect possible publication bias.

3. Results

3.1. Results of the search

Overall, after removal of the duplicates, 4796 papers were screened, of which 74 papers were found to be eligible for this review. However, following a search of the reference lists and citations (through Google Scholar) of the 74 included papers, 3 additional papers were identified as relevant. In total, 77 papers were included in this systematic review and meta-analysis. The search process is illustrated in Fig. 1.

Overall, 186 ESs were extracted from the 77 eligible studies. There were a total of 3870 participants with age = 27.2 ± 18.3 years (mean ± SD). Supplementary Table 1 presents the participant characteristics and outcomes of the included studies.

3.2. Risk of bias assessment and methodological quality

Fig. 2 shows the funnel plot, which includes all 77 studies in this meta-analysis. A visual inspection of the funnel plot and the Egger's regression intercept test (intercept = −3.96; $p < 0.001$) indicated reporting bias. The methodological quality, as assessed with the PEDro scale, revealed a range of scores between 4 and 10 points (out of 11) for all included studies. The average PEDro score value was 7.30 ± 1.09, indicating a low risk of bias.[33,34] The assessors agreed with 100% of the 847 criteria (77 studies × 11 scores). Mismatched outcomes were discussed, and the assessors agreed on the scores presented in Supplementary Table 2.

3.3. Overall effects

The meta-analysis on joint ROM revealed a moderate ES in favor of stretching compared to the control condition (ES = −1.002; Z = −12.07; 95% confidence interval (95%CI): −1.165 to −0.840; $p < 0.001$; I^2 = 74.97). Fig. 3 presents the forest plot of the meta-analysis, sorted by the standard difference in means.

3.4. Moderating variables

A summary of all the subgroup analyses is provided in Table 1. The subgroups analyzed were the muscles tested (sit and reach *vs*. isolated hamstrings *vs*. quadriceps *vs*. triceps surae *vs*. hip flexors *vs*. shoulder), intensity of stretch (high intensity *vs*. low intensity), trained state of the participants (recreationally active *vs*. professional athletes *vs*. sedentary), stretching techniques (static *vs*. dynamic/ballistic *vs*. PNF), supervision of the stretching intervention (fully supervised *vs*. periodically supervised *vs*. non-supervised), and sex (male *vs*. female).

Q statistics of the subgroup analysis revealed a significant difference for sex (p = 0.03). Although both sexes showed an increase in ROM ($p < 0.001$), the increase was more

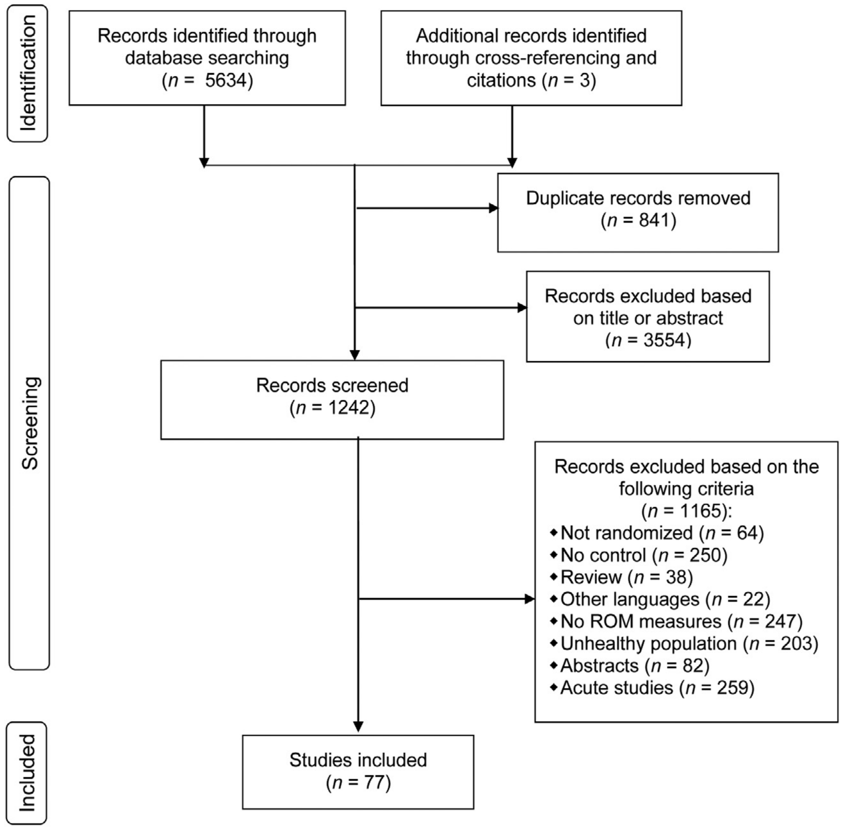

Fig. 1. Preferred Reporting Items for Systematic reviews and Meta-Analyses flowchart. ROM = range of motion.

pronounced in females (ES = −1.55) compared to males (ES = −0.88).

Moreover, Q statistics indicated a significant difference between the stretching techniques ($p = 0.012$). Further comparison showed no significant difference between static and PNF stretching techniques ($p = 0.28$) but a significantly greater ROM effect for static ($p = 0.01$) and PNF ($p = 0.01$) compared to ballistic/dynamic stretching, respectively. Further subgroup analyses revealed no significant difference in the Q statistics for the muscles tested ($p = 0.134$), intensity of stretch ($p = 0.540$), trained state of the participants ($p = 0.742$), stretching techniques ($p = 0.012$), and supervision of the stretching intervention ($p = 0.172$). Furthermore, meta-regression showed no relationship between the ESs for age ($R^2 = -0.03$; $p = 0.400$), total stretch duration ($R^2 = -0.03$; $p = 0.730$), or stretch frequency per week ($R^2 = -0.02$; $p = 0.420$), respectively.

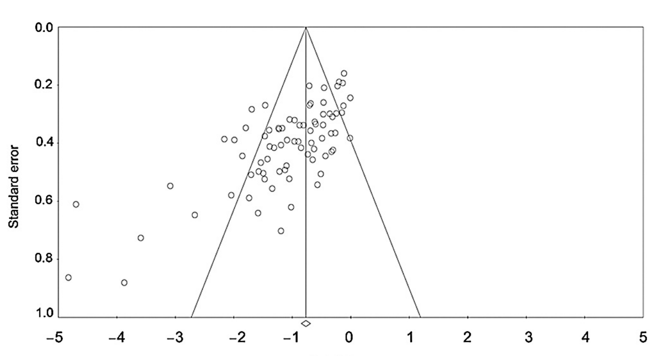

Fig. 2. Funnel plot analysis. Std diff = standard difference.

4. Discussion

The major finding of this meta-analysis was a main effect, overall, moderate magnitude (ES = −1.002; $p < 0.001$) increase in ROM compared to controls. Subgroup analysis indicated a significant difference in the effects between sexes and stretching techniques. However, further moderating analyses showed no other significant relationships or differences.

The finding of the main meta-analysis is in agreement with other meta-analyses[35,36] as well as other reviews[37] on the effects of stretch training on ROM. Moreover, subgroup analysis indicated a significant difference between the various stretching techniques ($p = 0.012$). Further pairwise comparison showed significantly greater ROM increases for PNF and static stretching compared to ballistic/dynamic stretching, respectively. However, there was no significant difference between static stretching and PNF stretching, although the ES for PNF stretching was slightly higher (ES = −1.280) compared to static stretching (ES = −1.005). These results are in accordance with a previous meta-analysis,[35] although PNF stretching provided a more pronounced increase compared to static stretching (mean difference of straight leg raise test 2.56°; $p = 0.30$).

Study name	Std diff in means	Z	p	Outcome
Feland et al. (2010)	-4.819	-5.574	0.000	Passive knee extension test ROM (active static stretching)
Simão et al. (2011)	-4.690	-7.659	0.000	Sit-and-reach test
Magalhães et al. (2015)	-3.864	-4.380	0.000	Combined
Chan et al. (2001)	-3.583	-4.921	0.000	Combined
Donti et al. (2021)	-3.078	-5.606	0.000	Hip hyperextension (static, Week 9)
Piqueras-Rodríguez et al. (2016)	-2.659	-4.096	0.000	Blank
Panidi et al. (2021)	-2.154	-5.553	0.000	Ankle dorsiflexion range of motion (static)
da Silva Gama et al. (2007)	-2.035	-3.503	0.000	Combined
De Baranda et al. (2010)	-1.982	-5.076	0.000	Combined
Gribble et al. (1999)	-1.846	-4.141	0.000	Combined
Moreside and McGill (2012)	-1.787	-5.119	0.000	Combined
Godges et al. (1993)	-1.730	-2.930	0.003	Combined
Covert et al. (2010)	-1.696	-3.324	0.001	Combined
Ayala et al. (2013)	-1.685	-5.907	0.000	Combined
Yildirim et al. (2016)	-1.578	-2.456	0.014	Combined
Hadjicharalambous (2016)	-1.567	-3.138	0.002	Sit-and-reach test
Cipriani et al. (2012)	-1.530	-3.264	0.001	Combined
Johnson et al. (2014)	-1.488	-2.945	0.003	Combined
Yuktasir and Kaya (2009)	-1.466	-2.788	0.005	Combined
Chepeha et al. (2018)	-1.463	-3.874	0.000	Combined
Ayala et al. (2010)	-1.455	-5.368	0.000	Combined
Batista et al. (2009)	-1.416	-3.101	0.002	Passive knee extension (static)
Santonja Medina et al. (2007)	-1.387	-3.886	0.000	Combined
Webright et al. (1997)	-1.379	-3.335	0.001	Active knee extension ROM
Roberts and Wilson (1999)	-1.335	-2.392	0.017	Combined
Gunaydin et al. (2020)	-1.304	-3.124	0.002	Combined
Li et al. (1996)	-1.227	-3.505	0.000	Combined
Kokkonen et al. (2007)	-1.219	-3.449	0.001	Sit-and-reach test
Melo et al. (2021)	-1.210	-2.424	0.015	Combined
Gajdosik et al. (2007)	-1.185	-1.684	0.092	Combined
Feland et al. (2001)	-1.185	-2.902	0.004	Combined
Bandy et al. (1997)	-1.165	-3.327	0.001	Combined
Gajdosik et al. (2005)	-1.118	-2.263	0.024	Dorsiflexion ROM (static)
Decicco et al. (2005)	-1.091	-2.276	0.023	Combined
Longo et al. (2021)	-1.082	-2.767	0.006	Passive dorsiflexion (passive static stretching)
Stanziano et al. (2009)	-1.044	-1.990	0.047	Combined
Rodríguez et al. (2008)	-1.037	-3.241	0.001	Combined
Lobel (2016)	-1.012	-1.627	0.104	Combined
Gallo et al. (2013)	-0.955	-2.415	0.016	Combined
Reid and McNair (2004)	-0.954	-2.956	0.003	Passive knee extension
Oba et al. (2021)	-0.889	-2.243	0.025	Passive dorsiflexion (isokinetic dynamometer)
Konrad and Tilp (2014a)	-0.868	-2.555	0.011	Dorsiflexion ROM
Ikeda et al. (2019)	-0.842	-2.017	0.044	Knee flexion ROM
Bandy et al. (1998)	-0.800	-2.354	0.019	Combined
Marshall et al. (2011)	-0.727	-1.650	0.099	Instrumented straight leg raise (static)
Becerra-Fernández et al. (2016)	-0.701	-3.436	0.001	Hamstring extensibility
Muyor et al. (2012)	-0.698	-2.574	0.010	Combined
González-Ravé et al. (2012)	-0.683	-1.904	0.057	Combined
Demoulin et al. (2016)	-0.678	-2.558	0.011	Combined
Nakamura et al. (2021)	-0.666	-1.661	0.097	Combined
Maciel and Câmara (2008)	-0.644	-1.405	0.160	Passive knee extension (static stretching)
Morton et al. (2011)	-0.620	-1.471	0.141	Combined
Konrad and Tilp (2014b)	-0.608	-1.852	0.064	Dorsiflexion ROM
Mayorga-Vega et al. (2017)	-0.593	-1.764	0.078	Hamstring extensibility
Halbertsma and Göeken (1994)	-0.562	-1.031	0.303	Passive instrumental straight leg raise
Williams et al. (2004)	-0.504	-0.992	0.321	Knee extension ROM
Lustig et al., (1992)	-0.483	-1.256	0.209	Combined
McClure et al. (2007)	-0.466	-1.373	0.170	Combined
Merino-Marban et al. (2015)	-0.463	-1.531	0.126	Sit-and-reach
Ben and Harvey (2010)	-0.459	-1.753	0.080	Passive hip flexion
Mayorga-Vega et al. (2016)	-0.449	-2.127	0.033	Combined
Blazevich et al. (2014)	-0.425	-0.954	0.340	Dorsiflexion range of motion
Mayorga-Vega et al. (2014)	-0.351	-1.169	0.242	Sit-and-reach
Barbosa et al. (2018)	-0.327	-0.888	0.375	Combined
da Costa et al. (2013)	-0.321	-0.745	0.456	Combined
Piqueras- Rodríguez et al. (2016)	-0.305	-0.982	0.326	Combined
Sermaxhaj et al. (2021)	-0.295	-0.694	0.488	Combined
Aquino et al. (2010)	-0.258	-0.704	0.482	Passive knee extension ROM
Mayorga-Vega et al. (2014)	-0.240	-0.801	0.423	Sit-and-reach
Kerrigan et al. (2003)	-0.219	-1.069	0.285	Combined
Mayorga-Vega et al. (2015)	-0.192	-1.005	0.315	Combined
Youdas et al. (2003)	-0.144	-0.485	0.628	Combined
Knapik et al. (2019)	-0.130	-0.667	0.505	Passive ankle dorsiflexion (goniometer)
Mahieu et al. (2007)	-0.118	-0.430	0.667	Combined
de Castro et al. (2013)	-0.107	-0.666	0.505	Combined
Swank et al. (2003)	-0.006	-0.015	0.988	Combined
Bybee et al. (2008)	0.000	0.000	1.000	Combined
	-1.002	-12.074	0.000	

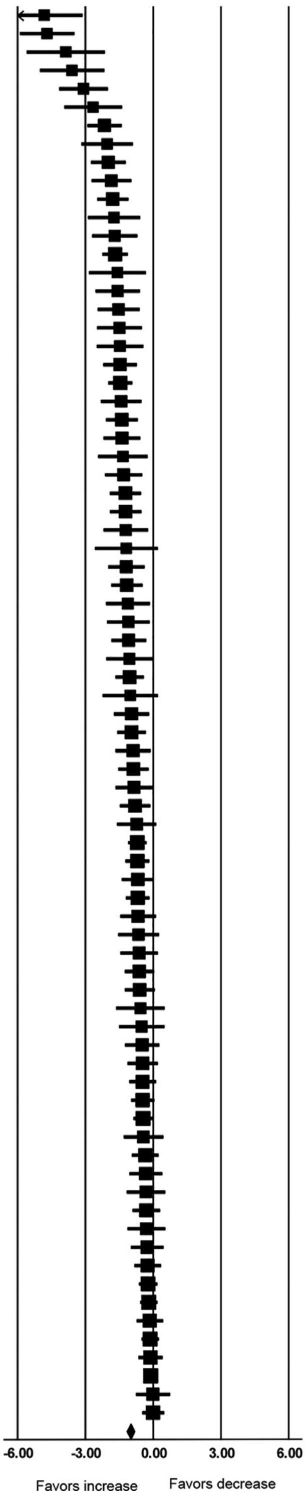

Fig. 3. Forest plot presenting the 77 included studies investigating the effects of stretching on range of motion. 95%CI = 95% confidence interval; ROM = range of motion; Std diff = standardized difference.

Controversially, another review that calculated the percentage change of ROM after stretching intervention pointed out that static stretching provided greater ROM increases compared to PNF and ballistic stretching.[37] Another meta-analysis in agreement with the current study concluded that PNF and static stretching induced greater ankle ROM improvements compared to ballistic stretching.[36] Based on the findings in the literature and our own analyses, ballistic or dynamic stretch training should not be applied if the goal is to maximize the ROM gains over the long-term. However, when dynamic stretching is

Table 1
Statistics of the subgroup analysis.

Subgroup	Number of measures	Std diff in means (95%CI)	p	Q statistics
Muscles tested				
Sit-and-reach	15	−0.849 (−1.187 to −0.511)	<0.001[a]	
Shoulder	6	0.739 (−1.122 to −0.356)	<0.001[a]	
Hamstrings	39	−1.155 (−1.379 to −0.931)	<0.001[a]	
Quadriceps	3	−0.616 (−1.280 to 0.049)	0.069	
Triceps surae	14	−0.696 (−1.006 to −0.387)	<0.001[a]	
Hip flexors	10	−1.134 (−1.843 to −0.425)	0.002[a]	
Overall	87	−0.925 (−1.066 to −0.784)	<0.001	$Q = 8.441$; $df = 5$; $p = 0.134$
Intensity of stretch				
Low intensity	32	−0.923 (−1.122 to −0.724)	<0.001[a]	
High intensity	24	−1.049 (−1.400 to −0.698)	<0.001[a]	
Overall	56	−0.954 (−1.127 to −0.781)	<0.001	$Q = 0.376$; $df = 1$; $p = 0.540$
Trained state				
Recreationally active	26	−1.253 (−1.585 to −0.921)	<0.001[a]	
Elite athlete	4	−1.296 (−2.413 to −0.179)	0.023[a]	
Sedentary	16	−1.044 (−1.482 to −0.606)	<0.001[a]	
Overall	46	−1.183 (−1.441 to −0.926)	<0.001	$Q = 0.597$; $df = 3$; $p = 0.742$
Stretching techniques				
Static	66	−1.005 (−1.184 to −0.825)	<0.001[a]	
Ballistic/dynamic	8	−0.550 (−0.852 to −0.248)	<0.001[a]	
PNF	11	−1.283 (−1.757 to −0.813)	<0.001[a]	
Overall	85	−0.925 (−1.095 to −0.778)	<0.001	$Q = 8.900$; $df = 2$; $p = 0.012$[b]
Sex				
Male	15	−0.886 (−1.225 to −0.546)	<0.001[a]	
Female	14	−1.558 (−2.088 to −1.028)	<0.001[a]	
Overall	29	−1.081 (−1.368 to −0.795)	<0.001	$Q = 4.381$; $df = 1$; $p = 0.036$[b]
Supervision of the stretching intervention				
Fully supervised	37	−1.081 (−1.329 to −0.833)	<0.001[a]	
Periodically supervised	12	−0.750 (−1.064 to −0.436)	<0.001[a]	
Not supervised	9	−0.740 (−1.139 to −0.340)	<0.001[a]	
Overall	58	−0.913 (−1.088 to −0.738)	<0.001	$Q = 3.525$; $df = 2$; $p = 0.172$

Note: Negative values of std diff in means indicates a favorable effect for stretching (and *vice versa*) on range of motion.
[a] Significant difference within a group.
[b] Significant difference between groups.
Abbreviations: 95%CI = 95% confidence interval; *df* = degree of freedom; PNF = proprioceptive neuromuscular facilitation; Std diff = standardized difference.

performed as a component of a warm-up with the goal to maximize performance, it is preferred compared to other stretching techniques.[3,6,18]

A potential explanation for why ballistic and dynamic stretching do not show such a high magnitude of change compared to PNF or static stretching might be found in the differences between the time under tension of the respective techniques. While during PNF or static stretching the joint is mainly in a stretched position throughout the whole stretching protocol, this is not the case during ballistic or dynamic stretching due to the swinging or bouncing movements. Consequently, different effect mechanisms might explain different changes in ROM with the respective stretching techniques. The 2 most common mechanisms for ROM increases are a decrease in tissue stiffness and/or increased stretch tolerance.[38,39] Considering ballistic stretch training for 6 weeks, no changes in soft tissue compliance (e.g., muscle stiffness) or muscle morphology (e.g., fascicle lengths, angles) were reported.[6,10,39] Similar to another 4-week ballistic-stretching intervention study,[40] an increase in pain or stretch tolerance is likely the main mechanism for the increase in ROM. Moreover, Mahieu et al.[19] reported no changes in passive resistive torque at the same angle following a 6-week stretching intervention with the ballistic technique. Surprisingly, they did find a decrease in tendon stiffness. Since passive resistive torque was kept constant at the same angle, it is likely that the decrease in tendon stiffness was compensated by an increase in muscle stiffness. Mahieu et al.[19] speculated, based on the assumption of McNair et al.,[41] that as a result of the cycling motion, polysaccharides and water were redistributed within the collagen framework of the tendon, which might have lead to a decrease in stiffness. With regard to PNF stretch training, a study reported no change in tendon stiffness,[20] while another reported a decrease in tendon stiffness (with no change in muscle stiffness) following a 6-week intervention period.[42] A possible explanation for such a decrease in tendon stiffness might be the changes that occur in the wave-like course of collagen fibers in an unstressed tendon, which become straightened when stretched.[43] Dozens of long-term stretching studies were published recently that consider the effect mechanisms of static stretching. It has been suggested that especially high-volume stretching must be applied to induce chronic changes in muscle-tendon unit properties (e.g., a decrease in muscle stiffness[13,28]), which can explain the

ROM increase. When considering lower stretching volumes, changes in the perception to stretch or stretch tolerance (rather than structural changes) are thought to be the mechanisms responsible for the increase in ROM following static stretch training over several weeks.[8,28]

Although the changes in muscle structure (e.g., stiffness) seem to be dependent on stretching volume, our meta-regression showed no significant relation between total stretch duration and ES on ROM ($R^2 = -0.03$; $p = 0.73$). The lack of a dose response is likely due to the fact that many of the studies conducted lower stretch durations (~1000 s), while only a few looked at a more comprehensive stretch duration. Another meta-analysis reported that the total stretching load had no impact on the magnitude of change in ankle ROM.[36] Even in a further meta-regression, we could not find a relation between stretch frequency per week and the effects sizes on ROM ($R^2 = -0.02$; $p = 0.42$). Based on these findings, it appears that stretching with a high volume and/or high weekly frequency might not be mandatory to maximize gains in ROM in the general population.

Stretching intensity was also considered as a potential moderating variable. An original study that directly compared high-intensity stretching with low-intensity stretching (i.e., without control groups) found a favorable ROM effect associated with the high-volume stretching techniques.[17] However, our subgroup analysis, which only took randomized controlled trials into consideration, found no significant difference between low- and high-intensity stretching in terms of ROM gains. Our results indicate that it might not be necessary to stretch to the pain threshold to maximize gains in ROM since with low intensity we found a significant moderate magnitude increase in ROM (ES = −0.92), while high-intensity stretching only showed a marginally better ES result (ES = −1.02). In contrast, the study done by Nakamura et al.[17] found significant differences between the intensities since the low-intensity protocol was 0−1 on a 11-point Verbal Numerical Scale compared to 6−7 for the high intensity. Hence, it can be assumed that a higher intensity than 0−1 has to be applied to get comparable results with a high-intensity approach. The studies in our meta-analysis tended to recruit recreationally active or trained subjects but not individuals who need extreme in ROM, such as gymnasts and figure skaters. The present findings regarding the insignificant effects of stretch intensity and duration may not equally apply when extreme flexibility is the goal; hence, further studies are needed to examine these distinct populations.

Concerning the supervision of the training, our subgroup analysis showed no significant difference between fully supervised, periodically, or non-supervised studies. However, concerning strength training regimes, it was reported that supervision can lead to superior results in outcome parameters such as strength compared to non-supervised training regimes.[44,45] While it is likely most of the eligible studies in our meta-analysis excluded non-committed participants, meaning those who failed to perform a certain percentage of the stretch training, it should still be noted that the fully supervised studies in our meta-analysis showed the highest ES (ES = −1.08) compared to periodically (ES = −0.75) or non-supervised (ES = −0.74) studies. Thus, future studies should take this into account and supervise participants throughout the stretch intervention period.

Concerning the trained state of the participants, our subgroup analysis showed no significant difference in ROM adaptations between elite athletes, recreational athletes, or sedentary individuals due to stretch training ($p = 0.74$). Since it was shown that trained and untrained individuals might respond differently to a training stimulus (i.e., concurrent resistance and endurance training),[46] we would not have expected similar adaptations. On the contrary, even the ESs within the groups were very similar and ranged from −1.253 to −1.044. As we know that various training regimes (e.g., strength training) can increase ROM,[47] future studies should take baseline flexibility levels into account when considering trained status as a variable.

Moreover, we also compared sex-specific responses of stretch training on ROM. Although it was no surprise that there was a significant difference in the subgroup analysis ($p = 0.036$), we initially thought that males would show higher ESs due to their lower baseline flexibility levels compared to females.[39,48] However, our results show the opposite, namely, significantly higher ESs in females (ES = −1.56) compared to males (ES = −0.88). A potential explanation for these results might be that females do not exhibit higher flexibility in all joints compared to males. McKay et al.,[25] for example, found similar values in males and females in ankle dorsiflexion ROM. Since the studies included in this meta-analysis frequently tested the ankle joint and found that at least the baseline values were equal, this is one potential explanation. However, it could also be that females react more sensitively to stretch training than males.

In terms of the individual muscles stretched, we saw no significant difference in our subgroup analysis ($p = 0.13$). Consequently, there seems to be no single muscle group that produces the greatest ROM increase. However, the ESs for the treated muscles range from −1.134 to −0.616, which indicates some variation between muscle groups/joints. For example, the ankle joint has a much more limited ROM than the hip or knee due to bone and ligament structures.[49,50] We would assume this limits the potential for long-term increases in ankle joint ROM. Indeed, by stretching the triceps surae, the ankle joint ROM increase showed a lower effect (−0.616) compared to hip or knee ROM (<−1.1) (i.e., by stretching the hamstrings or hip flexors). With the joint anatomical differences contributing to greater ankle joint restriction, it may be difficult to compare stretch-induced changes at the ankle to those at other joints, such as the hip. There may be a need for greater volumes or durations of stretch training with such restricted joints. We recommend that further research on muscle-specific adaptations is needed to obtain a clearer picture. Except for the quadriceps muscle and, hence, knee flexion flexibility, all treated muscles showed significant changes due to stretch training. A likely explanation for the lack in changes to the quadriceps muscle might be that only 3 ESs were available.

This meta-analysis has some limitations. First, a moderate to high heterogeneity was found in the main meta-analysis ($I^2 = 74.97$). This could be explained by varying outcome measures, participants, or intervention duration. Second, the visual inspection of the funnel plot as well as the significant Egger's regression intercept test (intercept = −3.96) indicated reporting bias. It is well known that significant positive results are more likely to be published, with an increased probability that they will be published in higher impact journals and, thus, achieve a higher number of citations.[51,52] Although one must always be cautious when interpreting results, especially those with a possibility of bias, the results of the main analysis of 77 studies did demonstrate moderate standardized differences in means (ES = −1.002).

5. Conclusion

This study was the first to perform a comprehensive meta-analysis on all joints and stretching techniques to allow a consideration of potential moderating factors, including stretching technique, intensity, duration, and muscles stretched, as well as sex-specific, age-specific, and/or trained state-specific adaptations to stretch training. The main meta-analysis showed an increase in ROM due to stretch training compared to the control groups. Subgroup analysis showed a significant difference between the stretching techniques and in the effects between the sexes. The finding that the volume, intensity, and weekly frequency of stretching might not play a significant role in ROM gains could be useful for sports practice as well as in future research.

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Authors' contributions

AK was involved in the idea conception, produced the figures and tables, performed the meta-analysis, and collaborated in writing the major parts of the manuscript; SA was involved in the idea conception and produced the figures and tables; DGB was involved in the idea conception and collaborated in writing the major parts of the manuscript. All authors collaborated on the literature review search and collection of data from their assigned articles and interpreting the results. 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 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.2023.06.002.

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