


SYSTEMATIC REVIEW

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# Acute Effects of Various Stretching Techniques on Range of Motion: A Systematic Review with Meta-Analysis

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## Abstract

**Background** Although stretching can acutely increase joint range of motion (ROM), there are a variety of factors which could influence the extent of stretch-induced flexibility such as participant characteristics, stretching intensities, durations, type (technique), and muscle or joint tested.

**Objective** The objective of this systematic review and meta-analysis was to investigate the acute effects of stretching on ROM including moderating variables such as muscles tested, stretch techniques, intensity, sex, and trained state.

**Methods** A random-effect meta-analysis was performed from 47 eligible studies (110 effect sizes). A mixed-effect meta-analysis subgroup analysis was also performed on the moderating variables. A meta-regression was also performed between age and stretch duration. GRADE analysis was used to assess the quality of evidence obtained from this meta-analysis.

**Results** The meta-analysis revealed a small ROM standard mean difference in favor of an acute bout of stretching compared to non-active control condition ( $ES = -0.555$ ;  $Z = -8.939$ ;  $CI (95\%) -0.677$  to  $-0.434$ ;  $p < 0.001$ ;  $I^2 = 33.32$ ). While there were ROM increases with sit and reach ( $P = 0.038$ ), hamstrings ( $P < 0.001$ ), and triceps surae ( $P = 0.002$ ) tests, there was no change with the hip adductor test ( $P = 0.403$ ). Further subgroup analyses revealed no significant difference in stretch intensity ( $P = 0.76$ ), trained state ( $P = 0.99$ ), stretching techniques ( $P = 0.72$ ), and sex ( $P = 0.89$ ). Finally, meta-regression showed no relationship between the ROM standard mean differences to age ( $R^2 = -0.03$ ;  $P = 0.56$ ) and stretch duration ( $R^2 = 0.00$ ;  $P = 0.39$ ), respectively. GRADE analysis indicated that we can be moderately confident in the effect estimates.

**Conclusion** A single bout of stretching can be considered effective for providing acute small magnitude ROM improvements for most ROM tests, which are not significantly affected by stretch intensity, participants' trained state, stretching techniques, and sex.

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## Key Points

- 1 The meta-analysis on joint range of motion (ROM) increases revealed a small effect size in favor of an acute bout of stretching compared to the control condition.
- 2 Subgroup analysis revealed a significant increase in ROM with sit and reach, hamstrings, and triceps surae tests, but no improvement with the hip adductor tests. Whereas all moderating variables presented significant increases in ROM, further subgroup analyses revealed no significant difference in ROM gains with the stretch intensity, trained state of the participants, stretching techniques, and sex.
- 3 A meta-regression showed no relationship between the effect sizes to age and stretch duration, respectively.

**Keywords** Flexibility, Stretch intensity, Stretch duration, Trained state, Sex, Age

## Introduction

Recent commentaries [1, 2] and systematic reviews [3, 4] have revealed that other types of stretching and other activities such as resistance training and foam rolling may provide similar acute improvements in range of motion (ROM) as static stretching. Whereas other techniques such as foam rolling can acutely and chronically improve ROM [5–8], stretching within a pre-activity warm-up is still a predominant preparation activity [9–13]. The controversy regarding performance impairments associated with prolonged static stretching as a pre-event (warm-up) activity led to a paradigm shift toward dynamic over static stretching [9–13]. However, recent reviews [9, 12, 13] have highlighted the limitations of this body of research. They have suggested that since an acute increase in ROM may benefit some sports performance and contribute to a decreased incidence of musculoskeletal injuries, especially with explosive and change of direction movements [14], appropriate durations (<60-s per muscle group) [9–13] of static stretching would still be a beneficial component of a warm-up. But, are all forms of stretching within a single session an effective means of improving ROM acutely, which may contribute to positive influences on fitness, health, or preparation for training and competition?

Some of the stretching variables affecting acute changes in ROM or flexibility are the type of stretch technique, intensity, duration, as well as the sex and trained state of the individual [9, 15]. All the various types of stretching techniques such as static stretching (SS), dynamic (DS), ballistic stretching, proprioceptive neuromuscular facilitation (PNF), and others can increase ROM [9, 16]. While SS involves lengthening a muscle until either a stretch sensation or the point of discomfort is reached and then holding the muscle in a lengthened position for a prescribed period of time [10, 11, 17, 18], DS uses a controlled movement through the ROM of the active

joint(s) [19]. Ballistic stretching differs from dynamic as it typically uses higher velocity movements with bouncing actions at the end of the ROM [20, 21]. There are two major forms of PNF stretching. The contract relax (CR) method involves a SS followed by an isometric contraction of the stretched muscle, with a subsequent stretch of the target muscle. The contract-relax-agonist contract method (CRAC) uses an additional contraction of the agonist muscle (i.e., opposing the muscle group being stretched) prior to an additional stretch of the target muscle [22, 23]. A number of studies suggest that PNF is more effective than SS or DS for improving ROM [24–26]. However, a recent meta-analysis reported greater ROMs achieved with SS over PNF training [27]. On the other hand, a number of studies report that a session of DS induced similar [28–30] or even greater [31, 32] ROM improvements than SS, while other articles show that an acute bout of SS is superior to DS [20, 33–36]. Thus, there is still no consistent clarity on whether there is a superior form of stretching to produce acute changes in ROM.

A number of acute stretching studies have shown that submaximal intensity stretches provide similar ROM benefits as near maximal point of discomfort stretches [37–41]. Apostolopoulos et al. [15] reviewed 79 articles mostly identified as low-quality studies with the objective to investigate the influence of stretch intensity on range of motion, delayed onset muscle soreness, and inflammation. With the lack of high-quality studies, the authors were unable to provide a definitive description regarding the impact of stretch intensity. Many of the stretching studies in their review did not describe the stretch intensity and those that did employ a wide variety of measures (e.g., point of discomfort, stretch to pain with the use of a therapist, maximum ROM with the use of a machine, therapist or a loaded stretch, maximum stretch with no pain). Cabido et al. [42] reported that the use of constant torque stretching (incremental

increases in joint angle during the stretch) induced higher stretch intensities than constant angle stretches (maintaining the joint angle during the stretch). They found higher ROM and lower passive muscle stiffness with constant torque stretching (higher intensity) versus constant angle stretching. Fukaya et al. [43] also compared five studies that implemented constant torque or angle stretches and concurred that constant torque stretches produced a greater ROM [42, 44–47]. They also examined 12 other studies and found that higher stretch intensities provided greater ROM in six of those studies [48–53]. Furthermore, they reported that five higher stretch intensity studies resulted in greater decreases in passive muscle stiffness [48, 52, 54–56], while three other studies showed no significant passive stiffness differences between stretching intensities. Hence, the effects of higher stretch intensities during an acute bout of stretching have not been demonstrated to be consistently more effective than lower stretch intensities in these studies. It would be important to quantify whether painful or uncomfortable stretching intensities are necessary to obtain the greatest acute increases in joint ROM. This information needs to be updated to provide the most recent developments in the field.

Nearly, all stretching duration can ameliorate ROM [9]. The inclusion of control conditions in ROM studies is vitally important since just testing ROM (typical duration for a single test could be less than 5-s) will improve ROM [57]. Roberts and Wilson [58] reported that nine stretches of 5-s each provided similar increases in passive ROM as three stretches of 15-s; however, the 15-s stretches provided significantly greater active ROM than the 5-s stretches. On the other hand, a number of researchers have recommended SS for 30–60-s to optimally improve passive ROM. [59–61]. A meta-analysis by Thomas et al. [27] suggested a minimum SS duration of 5 min per week for each muscle group. Thus, there seems to be a relatively wide range of SS durations that can provide significant improvements in joint ROM.

Baseline measures of flexibility are commonly reported to be greater for women than men [62–68], which may be partially attributed to differences in muscle mass, joint geometry, and higher musculotendinous stiffness in men [9, 16, 69]. Hoge et al. [70] reported that following nine passive SS repetitions of 135-s each, ROM increased for the women but not for the men. Not all studies illustrate female flexibility superiority. Lopes-Minnaro et al. [71] reported similar male sit and reach flexibility as women; however, the women showed 8% greater pelvic flexion. While women tend to possess significantly greater intrinsic levels of flexibility, the relative effect of a single

bout of SS may not be as disparate between sexes. Perhaps as men begin at a lower flexibility baseline, there is increased capacity for improvement. This relative effect needs further elucidation.

Therefore, the objective of this meta-analytical systematic review was to investigate the acute effects of stretching on ROM, with consideration of moderating variables such as stretching techniques, intensity, duration, as well as trained state or age of the participants, muscles tested, and sex.

## Methods

This review was conducted according to the 2020 PRISMA guidelines and the suggestions from Moher et al. [72] for systematic reviews with meta-analysis.

### Inclusion and Exclusion Criteria

In accord with PICOS (population, intervention, comparator, outcomes, study type) criteria, this review considered studies that investigated the intervention of an acute (single bout or session) effect of stretching on joint ROM (outcome) in healthy participants (population) compared to non-active control conditions (comparator). We included peer reviewed original studies published in English. The studies were included when they were either randomized controlled trials or controlled trials (type of studies). This implied that we excluded studies which were dealing with the training (chronic, long-term) effects of stretching, investigated any combined treatment (e.g., stretching combined with foam roller), or had another treatment as control condition (e.g., foam rolling). Moreover, we excluded review papers, case reports, special communications, letters to the editor, invited commentaries, conference papers, and theses.

### Search Strategy

An electronic literature search was performed in PubMed, Scopus, Web of Science, and SPORTDiscus. Papers were considered if they were published up to September 2022. 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.” (Additional file 1). The

systematic search was conducted by eight independent researchers (SA, AD, SH, AZ, RG, CE, CS, and AG). Initially, the articles were screened by their title and then abstract. If the content remained unclear, the full text was retrieved for further screening and identifying the relevant papers. Following this independent screening process, the researchers compared their findings. Disagreements were resolved by jointly reassessing the studies against the eligibility criteria.

### Extraction of the Data

From the 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 technique, stretch intensity, muscle stretched, muscle tested), and the results of the main variables (flexibility parameters) were extracted. For the flexibility parameters, pre- and post-intervention values plus standard deviations of the stretching and control groups were extracted. If some of the required data were missing in the included studies, the authors of the studies were contacted via email or similar channels (e.g., Research Gate). For studies with no available data, the corresponding authors were contacted. If no response was received from the corresponding authors, the studies were excluded.

### Risk of Bias Assessment

Egger's regression intercept test and visual inspection of the funnel plot were applied to detect possible publication bias.

### Methodological Quality

The methodological quality of the included studies was assessed using the PEDro scale. In total, 11 methodological criteria were rated by eight independent researchers (SA, AD, SH, AZ, RG, CE, CS, and AG). A point was given if the study met the eligibility criteria and evidently a score of zero was assigned if the criteria was not satisfied. Hence, higher scores indicated better methodological quality of the study. In the case of conflict between the eight researchers, the methodological criteria were reassessed and discussed.

### Confidence in the Cumulative Evidence

Grading of Recommendations, Assessment, Development and Evaluations (GRADE) rating analysis was used to assess the quality of the outcomes by using the GRADEpro Guideline Development Tool software (grade-pro.org). In general, GRADE has four levels of evidence quality: very low, low, moderate, and high. For GRADE

analysis, six evaluation components were adopted (study design, risk of bias, inconsistency of results, indirectness, imprecision, and others [publication bias, large effect, plausible confounding, and dose response gradient]).

### Statistics and Data Synthesis

The meta-analysis was performed using Comprehensive Meta-Analysis software, according to the recommendations of Borenstein et al. [73]. By applying a random-effect meta-analysis, we assessed the effect size in terms of the standardized mean difference. If any study reported more than one effect size, the mean of all the outcomes (effect sizes) within one study was used for the analysis and was defined as combined (as suggested by Borenstein et al. [73]). Moreover, by applying a mixed-effect model, we performed subgroup analyses. Although there is no general rule of thumb [73], we only performed subgroup analyses when there were  $\geq 3$  studies included in the respective subgroups. Consequently, we performed subgroup analyses for the muscles tested (sit and reach vs. isolated hamstrings vs. triceps surae vs. hip adductors), intensity of stretch (i.e., high intensity vs. low intensity), trained state of the participants (active vs. sedentary), stretching techniques (static vs. dynamic/ballistic vs. PNF), and sex (male vs. female). To determine differences between the effect sizes of the subgroups, Q-statistics were applied [73]. Moreover, to assess possible relations in the moderating variables, we conducted a meta-regression (i.e., age of the participants, stretch duration) based on the recommendations of Borenstein et al. [73]. According to the recommendations of Hopkins et al. [74], 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 the included studies, and thresholds of 25%, 50%, and 75% were defined as having a low, moderate, and high level of heterogeneity, respectively [75, 76]. An alpha level of 0.05 was defined for the statistical significance of all the tests. Data were presented in table and figure formats.

## Results

### Results of the Search

Overall, after removal of the duplicates, 4793 papers were screened, from which 42 papers were found to be eligible for this review (Table 1). After cross-referencing the included paper and their citation (via Google Scholar), of the 42 already included papers, five more papers were identified as relevant. Therefore, in total,

**Table 1** Study characteristics

Study	n	Age (years)	Sex	Trained State	Stretching Duration (s)	Stretched Muscle	Stretching Intensity	Outcome
Aguilar et al., 2012[93]	30	23	Mi	RA	600	Hamstrings	Below Maximum	Active and passive Hamstrings and hip flexors flexibility
Azevedo et al., 2011[94]	40	22.6	M	N/M	32	Hamstrings	Below Maximum	Hamstrings flexibility
Bacurau et al., 2009[20]	14	23.1	F	RA	540 & 1200	Quadriceps and Hamstrings	NR	Ballistic and static SR and hip flexors flexibility
Barbosa et al., 2018[95]	30	22.17	M	RA	180	Hamstrings	Below Maximum	Hams flexibility
César et al., 2016[96]	15	31.33	M	RA	90	Forearm Muscles	Maximum	Wrist hyperextension ROM
Chatzopoulos et al., 2019 [97]	24	15.08	F	RA	12 & 24 & 36	Hamstrings	NR	Active Hamstrings flexibility
Chen et al., 2013[98]	18	23.9	M	RA	210	Hamstrings	Below Maximum	Passive SLR
Lo et al., 2021[99]	20	20.7	Mi	E/P	150	Shoulder	Below Maximum	Shoulder internal rotation ROM
Coskunsu et al., 2021[100]	64	20.95	Mi	RA	120	Hamstrings	Maximum	Active SLR
Depino et al., 2000[101]	30	19.8	M	RA	120	Hamstrings	NR	Active Hamstrings flexibility
Espejo-Antunez et al., 2016[102]	42	21.5	Mi	RA	60	Hamstrings	Below Maximum	Passive Hamstrings flexibility
Hatano et al., 2022[91]	32	21.2	Mi	RA	300	Hamstrings	Below Maximum & Maximum	Passive Hamstrings flexibility
Hammer et al., 2017[103]	80	24.5	Mi	RA	120	Hip abductors	Below Maximum & Maximum	Hip abduction ROM
Hanney et al., 2017[104]	68	23.6	Mi	N/M	60	Trapezius	Maximum	Cervical ROM
Ikeda and Ryushi., 2019[105]	10	22	M	RA	900	Triceps surae	Below Maximum	Passive Dorsiflexion ROM
Kaneda et al., 2020[106]	17	23.2	M	S/U	120	Hamstrings	NR	Passive SLR ROM & Hamstrings flexibility
Konrad et al., 2017[45]	122	23.55	Mi	S/U	120	Triceps surae	Maximum	Dorsiflexion ROM
Konrad et al., 2019[107]	14	26.2	Mi	N/M	300	Triceps surae and Plantar Flexors	Maximum	Dorsiflexion ROM
Kuruma et al., 2013[108]	20	21	Mi	N/M	NR	Quadriceps	NR	Active and static Quadriceps flexibility
Lim et al., 2014[109]	32	22.5	M	S/U	28 & 30	Hamstrings	NR	Active Hamstrings flexibility
Maeda et al., 2016[110]	40	23.9	Mi	RA	120	Triceps surae	NR	Passive Dorsiflexion ROM
Maeda et al., 2017[111]	20	22.8	M	RA	120	Triceps surae	Maximum	Passive maximum DF ROM
Maeda et al., 2021[112]	30	23.5	M	N/M	300	Plantar Flexors	Maximum	Dorsiflexion ROM
Melo et al., 2021[113]	41	24.25	M	N/M	90	Hamstrings	Below Maximum & Maximum	Passive and active Hamstrings flexibility
Michaeli et al., 2017[114]	40	22.1	Mi	N/M	240	Hamstrings	NR	Static and dynamic SLR
Nishikawa et al., 2015[115]	108	20.3	Mi	RA	30	Hamstrings	Maximum	Active and passive Hamstrings flexibility
O'Hora et al., 2011[85]	30	25	Mi	N/M	30	Hamstrings	Maximum	Hams flexibility

**Table 1** (continued)

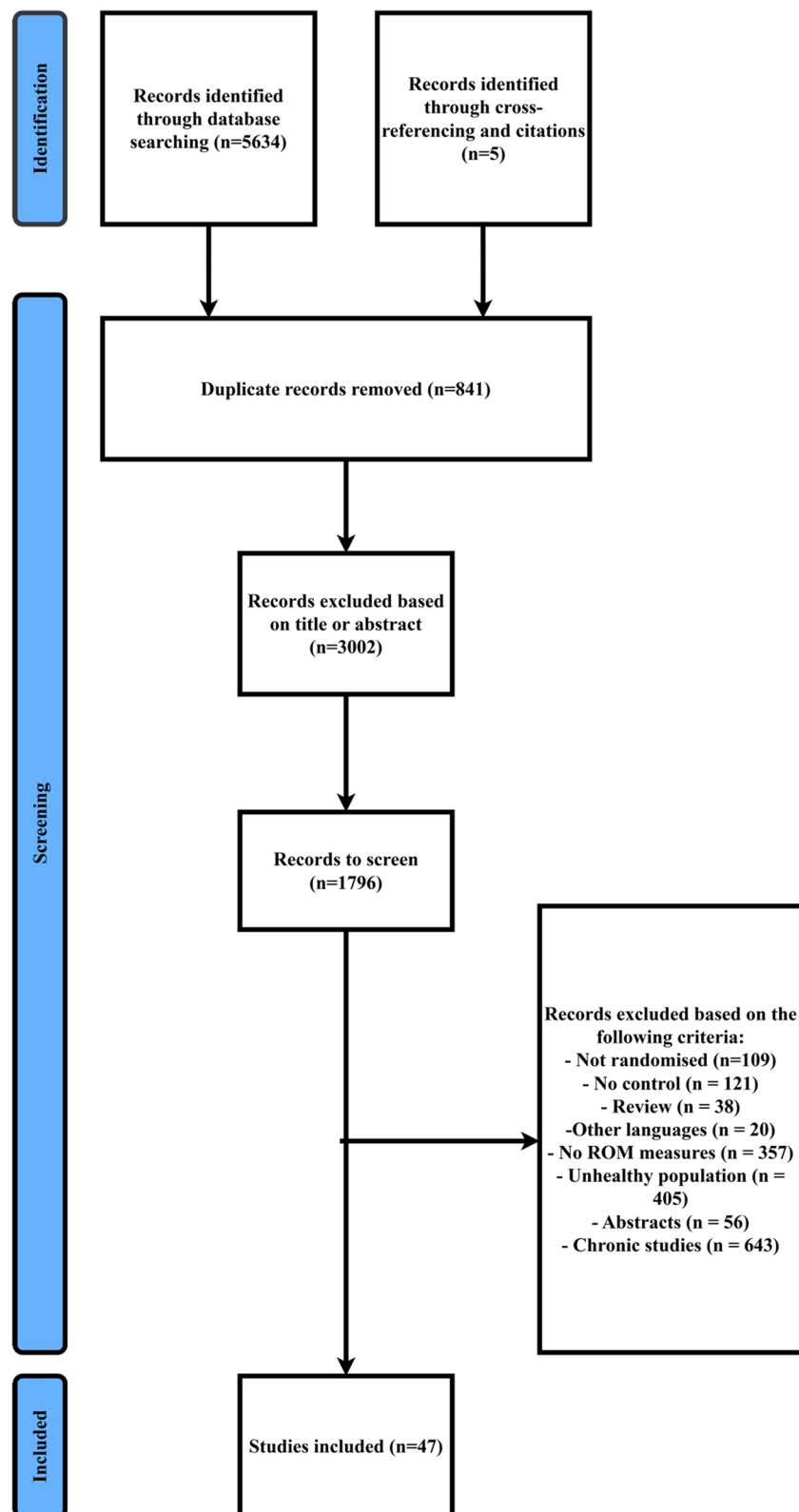
Study	n	Age (years)	Sex	Trained State	Stretching Duration (s)	Stretched Muscle	Stretching Intensity	Outcome
Pepper et al., 2021[116]	20	25.6	Mi	S/U	66	Hip adductors	Maximum	Passive hip adduction ROM
Pollard and Ward 1997[117]	40	NR	NR	N/M	20	Hamstrings	NR	Passive SLR
Pratt & Bohannon, 2003[118]	24	24.7	Mi	N/M	180	Gastrocnemius	NR	Passive Dorsiflexion ROM
Rodrigues et al., 2017[119]	24	22.1	M	S/U	120	Hamstrings	NR	Passive Hamstrings flexibility
Rowlett et al., 2019[120]	20	26.1	Mi	N/M	180	Gastrocnemius and Soleus	NR	Passive Dorsiflexion ROM
Rubini et al., 2011[121]	30	28.5	F	RA	360	Hip adductors	NR	Hip adductors flexibility
Rubley et al., 2011[122]	33	20.6	Mi	RA	90	Hamstrings	NR	Sit and reach
Ryan et al., 2014[123]	52	22.2	M	RA	360	Lower Extremity	Maximum	Dynamic Sit and Reach
Schuback et al., 2004[124]	26	35.8	Mi	N/M	120	Hamstrings	Maximum	Passive hip flexion ROM
Silva et al., 2012[125]	20	24	M	S/U	120	Hamstrings	Maximum	Active hip flexion ROM
Smith et al., 2018[126]	58	22	Mi	RA	900	Lower Extremity	NR	Dynamic Sit and Reach
Spernoga et al., 2001[127]	30	18.8	M	RA	300	Hamstrings	Below Maximum	Active Hamstrings flexibility
Vernette-Santana et al., 2015[128]	34	23	NR	RA	96	Hamstrings	NR	Passive and active SLR
Viveiros et al., 2004[129]	10	25	Mi	S/U	10 & 30 & 60 & 120 & 180 & 360	Posterior Deltoid	Maximum	Shoulder extension ROM
de Weijer et al., 2003[130]	28	25.4	Mi	N/M	90	Hamstrings	Below Maximum	Active Hamstrings flexibility
Wiemann & Hahn, 1997[131]	57	27	M	S/U	45	Hamstrings	NR	Static and ballistic hip flexion ROM
Yildiz et al., 2020[132]	35	23.6	M	RA	200	Calf, Quadriceps, Hip adductors, Hamstrings, Hip Rotators	Maximum	Sit and reach
Young et al. 2006[40]	20	22.8	Mi	RA	60 & 120 & 240	Triceps surae	Below Maximum & Maximum	Static Dorsiflexion ROM
Zakas et al., 2003[133]	47	14.7	Mi	RA	300	Hip adductors, Hamstrings, Quadriceps, Gastrocnemius, Hip Flexors, Spinal Extensor	Maximum	Passive hip flexion and extension, knee flexion, dorsiflexion, and trunk flexion ROM
Zito et al., 1997[134]	19	25.4	Mi	N/M	30	Gastrocnemius	Maximum	DF ROM

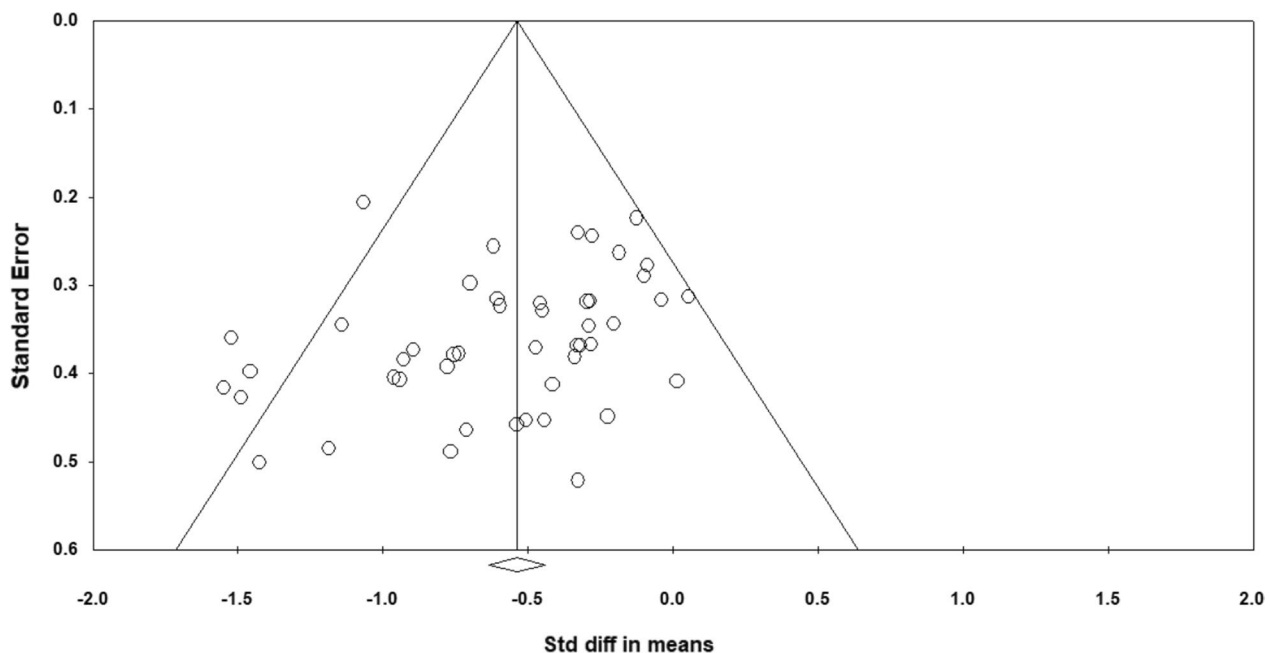
DF: dorsiflexion, F: female, M: male, Mi: mixed group of males and females, NR: not reported, ROM: range of motion, SLR: straight leg raise, SR: sit and reach, RA: recreationally active, S/U: sedentary or untrained,

47 papers were included in this systematic review and meta-analysis. The search process is illustrated in the PRISMA flow diagram (Fig. 1). We have not cited the 4746 studies that were excluded as the reference list would be untenable.

Overall, 110 effect sizes could be extracted from 47 eligible studies. In summary, 1658 participants with a mean age of 23.2 ( $\pm 3.4$  years) participated in the included studies. Table 1 presents the characteristics and outcomes of the 47 studies.



**Fig. 1** PRISMA flowchart



**Fig. 2** Funnel plot analysis. Std diff=Standard difference

#### Risk of Bias Assessment and Methodological Quality

Figure 2 shows the funnel plot, including all 47 studies in this meta-analysis. A visual inspection of the funnel plot and the Egger's regression intercept test (intercept  $-1.597$ ;  $P=0.04$ ) indicated reporting bias. The methodological quality, as assessed with the PEDro scale, revealed a range of scores between 5 and 9 points (out of 11) for all the included studies. The average PEDro score value was  $7.1 (\pm 0.9)$  (median and mode values = 7), indicating a low risk of bias [77, 78] (Additional file 2). The assessors agreed with 100% out of the 517 criteria (47 studies  $\times$  11 scores). The mismatched outcomes were discussed, and the assessors agreed on the scores presented in Table 1.

#### Confidence in Cumulative Evidence

For the study design, we have included randomized trials for the GRADE analysis. Risk of bias, indirectness, inconsistency, and imprecision showed no serious shortcomings. However, risk of bias assessment of the eligible studies showed publication bias as well as there was no large effect, no plausible confounding, and no dose response gradient. As a consequence, the analysis showed that we can be moderately confident in the effect estimates. This implies that the true effect is likely to be close to the estimate of the effect.

#### Overall Effects

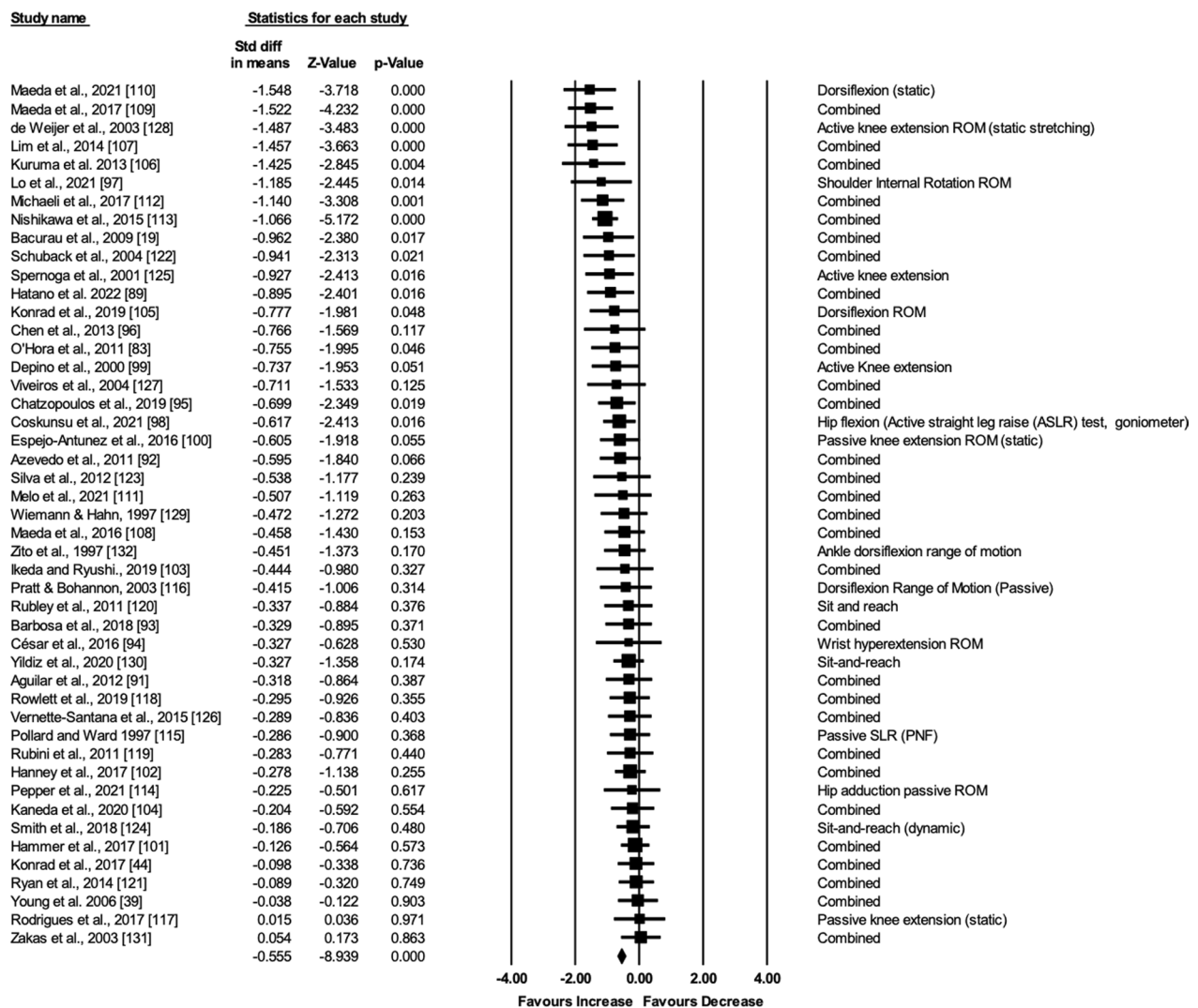
The meta-analysis on joint ROM revealed a small effect size in favor of stretching compared to the control condition ( $ES = -0.555$ ;  $Z = -8.939$ ;  $CI$  (95%)  $-0.677$  to  $-0.434$ ;  $p < 0.001$ ;  $I^2 = 33.32$ ). Figure 3 presents the forest plot of the meta-analysis, sorted by the standard difference in means beginning with the lowest value ( $-1.548$ ) up to the highest value ( $0.054$ ).

#### Moderating Variables

QA summary of all the subgroup analyses is provided in Table 2. The subgroups analyzed were the muscles tested (sit and reach (hamstrings and lower back) vs. isolated hamstrings vs. triceps surae vs. hip adductors), intensity of stretch (i.e., high intensity vs. low intensity), trained state of the participants (active vs. sedentary), stretching techniques (static vs dynamic/ballistic vs. PNF), and sex (male vs female).

Q-statistics of the subgroup analysis revealed a significant difference for the muscles tested ( $P = 0.003$ ). While there was an increase in ROM with the sit and reach test, hamstrings test, and triceps surae tests, no such change was seen in the hip adductor tests. Further subgroup analyses revealed no significant difference in the





**Fig. 3** Forest plot presenting the 47 included studies investigating the acute effects of a single bout or session of stretching on range of motion (ROM). Std diff in means = standardized difference in means; CI = confidence interval; combined = mean of the selected outcomes of one study. ROM: range of motion, SLR: straight leg raise, PNF: proprioceptive neuromuscular facilitation

**Table 2** Statistics of the subgroup analysis. Negative values of Std diff (= standardized difference) in means indicate a favorable effect for stretching (and vice versa) on range of motion

Subgroup	Number of measures	Std diff in means (95% CI)	P Value	Q-statistics
<i>Muscles tested</i>				
Sit and Reach	5	-0.272 (-0.529 to -0.016)	0.038 <sup>a</sup>	
Hamstrings	25	-0.674 (-0.831 to -0.518)	< 0.001 <sup>a</sup>	
Triceps surae	11	-0.504 (-0.821 to -0.187)	0.002 <sup>a</sup>	
Hip Adductors	4	-0.128 (-0.429 to 0.172)	0.403	
Overall	45	-0.495 (-0.609 to -0.381)	< 0.001	(Q = 13.67; df (Q) = 3; P = 0.003) <sup>b</sup>
<i>Intensity of stretch</i>				
High intensity	20	-0.570 (-0.782 to -0.358)	< 0.001 <sup>a</sup>	

**Table 2** (continued)

Subgroup	Number of measures	Std diff in means (95% CI)	P Value	Q-statistics
Low intensity	13	−0.524	(−0.735 to −0.312)	< 0.001 <sup>a</sup>
Overall	33	−0.547	(−0.697 to −0.397)	< 0.001
Trained state				(Q = 0.092; df (Q) = 1; P = 0.76)
Active	24	−0.496	(−0.655 to −0.337)	< 0.001 <sup>a</sup>
Sedentary	9	−0.499	(−0.825 to −0.173)	0.003 <sup>a</sup>
Overall	33	−0.496	(−0.639 to −0.353)	< 0.001
Stretching techniques				(Q = 0.000; df (Q) = 1; P = 0.98)
Static	36	−0.570	(−0.724 to −0.416)	< 0.001 <sup>a</sup>
Ballistic/Dynamic	10	−0.447	(−0.718 to −0.177)	0.001 <sup>a</sup>
PNF	9	−0.581	(−0.843 to −0.318)	< 0.001 <sup>a</sup>
Overall	55	−0.548	(−0.667 to −0.429)	< 0.001
				(Q = 0.667; df (Q) = 2; P = 0.72)
<b>Sex</b>				
Male	16	−0.607	(−0.853 to −0.361)	< 0.001 <sup>a</sup>
Female	3	−0.639	(−1.033 to −0.246)	0.001 <sup>a</sup>
Overall	19	−0.616	(−0.825 to −0.408)	< 0.001
				(Q = 0.019; df (Q) = 1; P = 0.89)

<sup>a</sup> = significant difference within a group<sup>b</sup> = significant difference between groups

Q-statistics for the stretch intensity ( $P = 0.76$ ), trained state of the participants ( $P = 0.99$ ), stretching techniques ( $P = 0.72$ ), and sex ( $P = 0.89$ ). Furthermore, meta-regression showed no relationship between the effect sizes to age ( $R^2 = -0.03$ ;  $P = 0.56$ ) and stretch duration ( $R^2 = 0.00$ ;  $P = 0.39$ ), respectively.

## Discussion

The major finding of this meta-analysis was a small magnitude effect size ROM increase with acute stretching compared to control conditions. GRADE analysis showed that we can be moderately confident in the effect estimates. The stretching-induced acute small magnitude increase in ROM is in accord with prior reviews that have reported that all four forms of stretching (SS, DS, ballistic, and PNF) can increase joint ROM [10, 22, 79]. Behm et al. [12] reported an overall 8.04% (Cohen's  $d = 0.55$ ) ROM increase from 27 SS studies, whereas Radford et al. [80] in their review of five studies concluded that plantar flexor muscle stretching induced small but significant increases in ankle dorsiflexion. Underlying acute stretching mechanisms have been attributed to an increased stretch (pain) tolerance [41, 112], decreased muscle stiffness [45, 49, 51, 109] thixotropic effects (decreased tissue viscoelasticity) [42], muscle spindle dysfacilitation (primarily with prolonged SS), pre-synaptic inhibition (as evidenced by reduced Hoffman reflexes) [81], and fascicle rotation [9, 10, 82].

## Stretching Technique

The present review did not find any ROM differences based on the stretching technique. There are diverse reports indicating greater [83–85] or similar ROM increases with PNF vs. SS [86, 87] as well as similar [28, 29] or greater [31, 32] increases in flexibility with DS vs. SS. These findings contrast with other studies reporting that DS was not as effective for increasing ROM as SS [20, 33–36]. When examining 55 effect sizes (SS: 36, ballistic/DS: 10, PNF: 9 studies) with disparate stretch intensities, durations and other prescription components, the main message from this review is that all forms of stretching are similarly effective in promoting acute increases in joint ROM within a general population.

## Stretch Duration

Whereas the included studies with these 55 effect sizes used a wide variety of stretch durations, there was no significant difference in ROM gains based on stretch duration. ROM can be augmented with stretch durations as short as 5-s [57]. Nine stretches of 5-s induced similar increases in passive ROM as three stretches of 15-s; however, the longer duration stretches provided significantly higher active ROM than the shorter duration stretches [58]. Johnson et al. [88] did not find any knee extension ROM differences whether participants trained with nine repetitions of 10-s or three repetitions of 30-s. A systematic review of four studies [58, 59, 89, 90] by DeCoster et al. [79] indicated that while a stretching bout of 30-s

might be most effective, durations greater than 30-s do not provide an additional ROM advantage. Studies employing increased stretch repetitions with shorter durations provided similar ROM improvements [58, 90]. A number of studies have recommended 30–60-s of SS to optimally improve ROM. [59–61]. Thus, while there is a spectrum of stretch durations that can significantly increase joint ROM, the present analysis indicates that there is no single duration that provides a significant ROM gain advantage.

### Stretch Intensity

Similarly, using a high or low stretch intensity did not significantly modulate ROM gains. One of the difficulties in analyzing stretch intensity is the lack of consistency in the description of intensity (e.g., point of discomfort, stretch to pain, maximum ROM with the use of a machine to maintain constant torque or constant angle, maximum stretch with no pain). While Apostolopoulos et al. [15] reviewed 79 articles of mostly low-quality studies, they were not able to definitively judge the impact of stretch intensity on joint ROM. A number of acute stretching studies have shown that submaximal intensity stretches provide similar ROM benefits as near maximal point of discomfort stretches [37–41]. Two reviews [42, 43] reported that constant torque stretching (higher intensity) induced greater ROM and lower passive muscle stiffness than constant angle (lower intensity) stretching. In the Fukaya et al. [43] review, only six of 12 other studies reported greater ROM with higher stretch intensity, and only five of eight higher stretch intensity studies reported greater decreases in passive muscle stiffness. Hatano et al. [91] reported a positive correlation between stretching intensity and the degree of change in ROM and muscle stiffness. Hence, while there is some evidence illustrating greater effectiveness for improving ROM with higher intensity stretching, the results of the present review reflect the overall variability in the literature. While many coaches in sports necessitating extreme ROM like gymnastics, wrestling, and figure skating anecdotally are proponents of higher stretch intensities to attain these high ROMs, the present review of the population in general did not reveal a positive association. Furthermore, one must be cautious as high stretching intensity may exacerbate inflammation in chronic clinical conditions while improving the ROM of soft and connective tissue in therapeutic and athletic populations [15].

### Muscles Tested

An acute bout of stretching will increase ROM in most tests (i.e., sit and reach (hamstrings and lower back),

isolated hamstrings, and triceps surae ROM tests) with the exception of hip adductor [114, 119] and abductor [101, 131] ROM tests. Changes in hip adduction and abduction may be more limited by the skeletal configuration of the acetabulum inhibiting ROM increases to a greater degree than other joint movements with greater excursions. Furthermore, to limit motion and prevent dislocations, the thickness and volume of connective tissue is more extensive at the hip to maintain joint integrity during weight bearing movements, as compared to other joints such as the shoulder, which has greater range of motion and is not often not weight bearing. In addition, the hip adductor and abductor muscles commonly do not experience as expansive a ROM with activity as the hip flexors or extensors (e.g., with sprinting, jumping, bounding), and thus, the hip adductors and abductors might be less sensitive to increases in ROM. Finally, when considering the subgroup analysis of the respective muscles, it has to be noted that only two effect sizes each for the hip adductors and abductors were included, and hence, caution has to be taken not to overemphasize the results found.

### Participant Characteristics

The trained state, age, or sex of the participant did not present significant differences in ROM gains. Similarly, a recent meta-analysis comparing the effects of stretching and foam rolling on ROM reported no significant differences between participants' age groups, activity levels, tested muscle by the ROM test (hamstrings, quadriceps, triceps surae, deltoid), stretch or foam rolling duration, sex, stretching technique (SS, DS), and the study design (parallel design, crossover) [6]. Furthermore, another meta-analysis examining crossover and non-local effects on ROM from unilateral, acute, passive, static stretching showed moderate magnitude increases in non-local (non-stretched) joint ROM in healthy young adults with no significant differences between trained state, stretching intensity, and sex [76]. Although stretching duration did not demonstrate significant differences in this Behm et al. meta-analysis [76], more than 240-s of stretching exhibited large magnitude increases in non-local ROM compared to only moderate magnitude improvements with lower (<240- and <120-s) stretching durations.

An initial thought might contend that the lower baseline levels of flexibility with untrained individuals would give them a greater training capacity for ROM improvements. However, when considering the capacity for extreme improvements in ROM seen with certain athletes (e.g., figure skaters, gymnasts, divers, contortionists), the extent of change is capacious. Thus, even with

higher baseline flexibility, trained individuals still have extensive potential for increased ROM that would not differentiate them from untrained individuals with a single (acute) session of stretching [92].

Although older individuals tend to exhibit more restricted ROM [25, 84], relative increases in ROM with stretch training have been reported to be similar to younger adults [84], and they demonstrate greater degrees of flexibility than untrained older adults [84]. Moreover, women tend to have greater joint ROM than men [62–67] due to differences in muscle mass, joint geometry, and the degree of collagen in the musculo-tendinous unit [16]. Hence, the present results suggest that even when the baseline flexibility is more limited in untrained young or older adults or males compared to females, the potential for acute ROM increases is not hindered by age, sex, or trained state.

### Limitations

Limitations in the research included that not all muscle groups are equally represented in the literature, and further research should expand the scope of muscles tested as for example the limited research on hip adductors. Almost every study described in this review recruited young adults, and only two studies focused solely on females; hence a wider spectrum of participants needs to be investigated.

### Conclusions

This systematic review and meta-analysis demonstrated a small magnitude increase in ROM with stretching compared to the control condition. Acute increases in ROM occurred with all muscles tested (sit and reach, hamstrings, and triceps surae tests), but no improvement with the hip adductor tests, which might be attributed to more natural anatomical and functionally restricted movement patterns. There was also no significant difference in ROM gains with the stretch intensity, duration, trained state of the participants, stretching techniques, age, or sex suggesting relative acute increases in ROM possess a broad capacity for acute improvement. Consequently, it can be suggested that all types of stretching can be implemented acutely for diverse populations (i.e., male and female, trained and untrained individuals) with similar results expected.

### Abbreviations

CRAC	Contract-relax-agonist contract
DS	Dynamic stretching
ES	Effect size
ROM	Range of motion
PNF	Proprioceptive neuromuscular facilitation
SS	Static stretching

## Supplementary Information

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**Additional file 1.** Search Strategy.

**Additional file 2.** Table S1: PEDro scales.

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### Author contributions

AK, AD, SA, and DB were involved in the idea conception. AK and SA collaborated on organizing the data collection from the literature review. Article search, selection, and data collection were performed by SA, AD, SHA, AG, AZ, RG, CE, RC, and CS. AK performed the meta-analysis. All authors collaborated on interpreting the results. DB and AK collaborated in writing the major parts of the manuscript. All authors contributed to the article, approved the submitted version, and read and approved the final manuscript.

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### Availability of data and materials

All data will be made available on request to the corresponding author.

### Code availability

Not applicable.

### Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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### References

1. Nuzzo JL. The case for retiring flexibility as a major component of physical fitness. *Sports Med.* 2020;50(5):853–70.
2. Afonso J, Olivares-Jabalera J, Andrade R. Time to move from mandatory stretching? We need to differentiate "Can I?" From "Do I Have To?" *Front Physiol.* 2021;12: 714166.
3. Afonso J, Ramirez-Campillo R, Moscaio J, Rocha T, Zacca R, Martins A, et al. strength training versus stretching for improving range of motion: a systematic review and meta-analysis. *Healthcare (Basel).* 2021;9(4).
4. Alizadeh SD, Zahir A, Hadjizadeh Anvar S, Goudini R, Hicks JP, Konrad A, Behm DG. Resistance training induces improvements in range of

- motion: a systematic review and meta-analysis. *Sports Med.* 2023. <https://doi.org/10.1007/s40279-022-01804-x>.
5. Konrad A, Nakamura M, Bernsteiner D, Tilp M. The Accumulated effects of foam rolling combined with stretching on range of motion and physical performance: a systematic review and meta-analysis. *J Sports Sci Med.* 2021;20(3):535–45.
  6. Konrad A, Nakamura M, Paternoster FK, Tilp M, Behm DG. A comparison of a single bout of stretching or foam rolling on range of motion in healthy adults. *Eur J Appl Physiol.* 2022;122(7):1545–57.
  7. 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(10):2523–35.
  8. Konrad A, Tilp M, Nakamura M. A comparison of the effects of foam rolling and stretching on physical performance. A systematic review and meta-analysis. *Front Physiol.* 2021;12:72053.
  9. Behm DG. The science and physiology of flexibility and stretching: implications and applications in sport performance and health. London, UK: Routledge Publishers; 2018.
  10. 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):1–11.
  11. Behm DG, Chaouachi A. A review of the acute effects of static and dynamic stretching on performance. *Eur J Appl Physiol.* 2011;111(11):2633–51.
  12. 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(1):67–94.
  13. Chaabene H, Behm DG, Negra Y, Granacher U. Acute effects of static stretching on muscle strength and power: an attempt to clarify previous caveats. *Front Physiol.* 2019;10:1468.
  14. Behm DG, Trajano ADGS, Alizadeh S, Blazevich AJ. Effects of stretching on injury risk reduction and balance. *J Clinical Exerc Physiol.* 2021;10(3):106–16.
  15. Apostolopoulos N, Metsios GS, Flouris AD, Koutedakis Y, Wyon MA. The relevance of stretch intensity and position—a systematic review. *Front Psychol.* 2015;6:1128.
  16. Alter MJ. *Science of Flexibility*. Champaign Illinois: Human Kinetics; 1996.
  17. 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(2):89–96.
  18. Behm DG, Bambury A, Cahill F, Power K. Effect of acute static stretching on force, balance, reaction time, and movement time. *Med Sci Sports Exerc.* 2004;36(8):1397–402.
  19. Fletcher IM. The effect of different dynamic stretch velocities on jump performance. *Eur J Appl Physiol.* 2010;109(3):491–8.
  20. Bacurau RF, Monteiro GA, Ugrinowitsch C, Tricoli V, Cabral LF, Aoki MS. Acute effect of a ballistic and a static stretching exercise bout on flexibility and maximal strength. *J Strength Cond Res.* 2009;23(1):304–8.
  21. Nelson AG, Kokkonen J. Acute ballistic muscle stretching inhibits maximal strength performance. *Res Q Exerc Sport.* 2001;72(4):415–9.
  22. Sharman MJ, Cresswell AG, Riek S. Proprioceptive neuromuscular facilitation stretching: mechanisms and clinical implications. *Sports Med.* 2006;36(11):929–39.
  23. Sady SP, Wortman M, Blanke D. Flexibility training: ballistic, Static or proprioceptive neuromuscular facilitation? *Arch Physical Med Rehabil.* 1982;63:261–3.
  24. Osternig L, Robertson R, Troxel R, Hansen P. Differential responses to proprioceptive neuromuscular facilitation (PNF) stretch techniques. *Med Sci Sports Exerc.* 1990;22(1):106–11.
  25. Gonzalez-Rave JM, Sanchez-Gomez A, Santos-Garcia DJ. Efficacy of two different stretch training programs passive vs. proprioceptive neuromuscular facilitation on shoulder and hip range of motion in older people. *J Strength Cond Res.* 2012;26:1045–51.
  26. Hindle KB, Whitcomb TJ, Briggs WO, Hong J. Proprioceptive neuromuscular facilitation (PNF): Its mechanisms and effects on range of motion and muscular function. *J Human Kinetics.* 2012;31:105–13.
  27. 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(4):243–54.
  28. Beedle BB, Mann CL. A comparison of two warm-ups on joint range of motion. *J Strength Cond Res.* 2007;21(3):776–9.
  29. Perrier ET, Pavol MJ, Hoffman MA. The acute effects of a warm-up including static or dynamic stretching on countermovement jump height, reaction time, and flexibility. *J Strength Cond Res.* 2011;25(7):1925–31.
  30. Matsuo S, Iwata M, Miyazaki M, Fukaya T, Yamanaka E, Nagata K, et al. Changes in flexibility and force are not different after static versus dynamic stretching. *Sports Med Int Open.* 2019;3(3):E89–95.
  31. Duncan MJ, Woodfield LA. Acute effects of warm-up protocol on flexibility and vertical jump in children. *J Exerc Physiol.* 2006;9(3):9–16.
  32. Amiri-Khorasani M, Abu Osman NA, Yusof A. Acute effect of static and dynamic stretching on hip dynamic range of motion during instep kicking in professional soccer players. *J Strength Cond Res.* 2011;25(6):1647–52.
  33. Paradisis GP, Pappas PT, Theodorou AS, Zacharogiannis EG, Skordilis EK, Smirniotou AS. Effects of static and dynamic stretching on sprint and jump performance in boys and girls. *J Strength Cond Res.* 2014;28(1):154–60.
  34. Samuel MN, Holcomb WR, Guadagnoli MA, Rubley MD, Wallmann H. Acute effects of static and ballistic stretching on measures of strength and power. *J Strength Cond Res.* 2008;22(5):1422–8.
  35. Sekir U, Arabaci R, Akova B, Kadagan SM. Acute effects of static and dynamic stretching on leg flexor and extensor isokinetic strength in elite women athletes. *Scand J Med Sci Sports.* 2010;20(2):268–81.
  36. Barroso R, Tricoli V, Santos Gil SD, Ugrinowitsch C, Roschel H. Maximal strength, number of repetitions, and total volume are differently affected by static-, ballistic-, and proprioceptive neuromuscular facilitation stretching. *J Strength Cond Res.* 2012;26(9):2432–7.
  37. Knudson D, Bennett K, Corn R, LeickSmith DC. Acute effects of stretching are not evident in the kinematics of the vertical jump. *J Strength Cond Res.* 2001;15(1):98–101.
  38. Knudson DV, Noffal GJ, Bahamonde RE, Bauer JA, Blackwell JR. Stretching has no effect on tennis serve performance. *J Strength Cond Res.* 2004;18(3):654–6.
  39. Manoel ME, Harris-Love MO, Danoff JV, Miller TA. Acute effects of static, dynamic, and proprioceptive neuromuscular facilitation stretching on muscle power in women. *J Strength Cond Res.* 2008;22(5):1528–34.
  40. Young W, Elias G, Power J. Effects of static stretching volume and intensity on plantar flexor explosive force production and range of motion. *J Sports Med Physical Fitness.* 2006;46(3):403–11.
  41. Behm DG, Kibele A. Effects of differing intensities of static stretching on jump performance. *Eur J Appl Physiol.* 2007;101(5):587–94.
  42. Cabido CE, Bergamini JC, Andrade AG, Lima FV, Menzel HJ, Chagas MH. Acute effect of constant torque and angle stretching on range of motion, muscle passive properties, and stretch discomfort perception. *J Strength Cond Res.* 2014;28(4):1050–7.
  43. Fukaya T, Sato S, Yahata K, Yoshida R, Takeuchi K, Nakamura M. Effects of stretching intensity on range of motion and muscle stiffness: a narrative review. *J Bodyw Mov Ther.* 2022;32:68–76.
  44. Herda TJ, Costa PB, Walter AA, Ryan ED, Hoge KM, Kerksick CM, et al. Effects of two modes of static stretching on muscle strength and stiffness. *Med Sci Sports Exerc.* 2011;43(9):1777–84.
  45. Konrad A, Budini F, Tilp M. Acute effects of constant torque and constant angle stretching on the muscle and tendon tissue properties. *Eur J Appl Physiol.* 2017;117(8):1649–56.
  46. Palmer TB. Acute effects of constant-angle and constant-torque static stretching on passive stiffness of the posterior hip and thigh muscles in healthy, young and old men. *J Strength Cond Res.* 2019;33(11):2991–9.
  47. Yeh CY, Tsai KH, Chen JJ. Effects of prolonged muscle stretching with constant torque or constant angle on hypertonic calf muscles. *Arch Phys Med Rehabil.* 2005;86(2):235–41.
  48. Takeuchi K, Nakamura M. Influence of high intensity 20-second static stretching on the flexibility and strength of hamstrings. *J Sports Sci Med.* 2020;19(2):429–35.

49. Oba K, Samukawa M, Nakamura K, Mikami K, Suzumori Y, Ishida Y, et al. Influence of constant torque stretching at different stretching intensities on flexibility and mechanical properties of plantar flexors. *J Strength Cond Res*. 2021;35(3):709–14.
50. Nakamura M, Sato S, Murakami Y, Kiyono R, Yahata K, Sanuki F, et al. The comparison of different stretching intensities on the range of motion and muscle stiffness of the quadriceps muscles. *Front Physiol*. 2020;11: 628870.
51. Kataura S, Suzuki S, Matsuo S, Hatano G, Iwata M, Yokoi K, et al. Acute effects of the different intensity of static stretching on flexibility and isometric muscle force. *J Strength Cond Res*. 2017;31(12):3403–10.
52. Fukaya T, Kiyono R, Sato S, Yahata K, Yasaka K, Onuma R, et al. Effects of static stretching with high-intensity and short-duration or low-intensity and long-duration on range of motion and muscle stiffness. *Front Physiol*. 2020;11: 601912.
53. Fukaya T, Matsuo S, Iwata M, Yamanaka E, Tsuchida W, Asai Y, et al. Acute and chronic effects of static stretching at 100% versus 120% intensity on flexibility. *Eur J Appl Physiol*. 2021;121(2):513–23.
54. Santos CXB, N.B.; Torres Piraua, A.L.; Quagliotto Durigan, J.L.; Behm, D.G.; Cappato de Araujo, R. Static stretching intensity does not influence acute range of motion, passive torque, and muscle architecture. *J Sport Rehabil*. 2020;29:1–6.
55. Beltrao NB, Ximenes Santos C, de Oliveira VMA, Piraua ALT, Behm D, Pitangui ACR, et al. Effects of a 12-week chronic stretch training program at different intensities on joint and muscle mechanical responses: a randomized clinical trial. *J Sport Rehabil*. 2020;29(7):904–12.
56. Muanjai P, Jones DA, Mickevicius M, Satkunskiene D, Snieckus A, Rutkauskaitė R, et al. The effects of 4 weeks stretching training to the point of pain on flexibility and muscle tendon unit properties. *Eur J Appl Physiol*. 2017;117(8):1713–25.
57. Grabow L, Young JD, Alcock LR, Quigley PJ, Byrne JM, Granacher U, et al. Higher quadriceps roller massage forces do not amplify range-of-motion increases nor impair strength and jump performance. *J Strength Cond Res*. 2018;32(11):3059–69.
58. Roberts JM, Wilson K. Effect of stretching duration on active and passive range of motion in the lower extremity. *Br J Sports Med*. 1999;33(4):259–63.
59. Bandy WD, Irion JM. The effect of time on the static stretch of the hamstrings muscles. *Phys Ther*. 1994;74(9):845–50.
60. Chan SP, Hong Y, Robinson PD. Flexibility and passive resistance of the hamstrings of young adults using two different static stretching protocols. *Scand J Med Sci*. 2001;11:81–6.
61. Feland JB, Myrer JW, Schulthies SS, Fellingham GW, Measom GW. The effect of duration of stretching of the hamstring muscle group for increasing range of motion in people aged 65 years or older. *Phys Ther*. 2001;81(5):1110–7.
62. Youdas JW, Krause DA, Hollman JH, Harmsen WS, Laskowski E. The influence of gender and age on hamstring muscle length in healthy adults. *J Orthop Sports Phys Ther*. 2005;35(4):246–52.
63. Soucie JM, Wang C, Forsyth A, Funk S, Denny M, Roach KE, et al. Range of motion measurements: reference values and a database for comparison studies. *Haemophilia*. 2011;17(3):500–7.
64. Allander E, Björnsson OJ, Olafsson O, Sigfusson N, Thorsteinsson J. Normal range of joint movements in shoulder, hip, wrist and thumb with special reference to side: a comparison between two populations. *Int J Epidemiol*. 1974;3(3):253–61.
65. Gabbard CT, R. Body composition and flexibility among prepubescent males and females. *J Human Movement Studies*. 1988;4(14):153–9.
66. Haley SM, Tada WL, Carmichael EM. Spinal mobility in young children. A normative study. *Phys Ther*. 1986;11:1697–703.
67. Jones MAB, J. M.; Harris, J. D. Relationship of race and sex to physical and motor measures. *Perceptual Motor Skills* 1986 1: 169–70.
68. Mier CM, Shapiro BS. Sex differences in pelvic and hip flexibility in men and women matched for sit-and-reach score. *J Strength Cond Res*. 2013;27(4):1031–5.
69. Morse CI. Gender differences in the passive stiffness of the human gastrocnemius muscle during stretch. *Eur J Appl Physiol*. 2011;111(9):2149–54.
70. Hoge KM, Ryan ED, Costa PB, Herda TJ, Walter AA, Stout JR, et al. Gender differences in musculotendinous stiffness and range of motion after an acute bout of stretching. *J Strength Cond Res*. 2010;24(10):2618–26.
71. Lopez-Minarro PA, Andujar PS, Rodríguez-García PL. A comparison of the sit-and-reach test and the back-saver sit-and-reach test in university students. *J Sports Sci Med*. 2009;8(1):116–22.
72. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *J Clin Epidemiol*. 2009;62(10):1006–12.
73. Borenstein M, Hedges LV, Higgins JP, Rothstein HR. A basic introduction to fixed-effect and random-effects models for meta-analysis. *Res Synth Methods*. 2010;1(2):97–111.
74. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3–12.
75. Higgins JP, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. *BMJ*. 2003;327(7414):557–60.
76. Behm DG, Alizadeh S, Anvar SH, Drury B, Granacher U, Moran J. Non-local acute passive stretching effects on range of motion in healthy adults: a systematic review with meta-analysis. *Sports Med*. 2021;51(5):945–59.
77. 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(8):713–21.
78. Moran J, Ramirez-Campillo R, Liew B, Chaabene H, Behm DG, Garcia-Hermoso A, et al. Effects of bilateral and unilateral resistance training on horizontally orientated movement performance: a systematic review and meta-analysis. *Sports Med*. 2020.
79. Decoster LC, Cleland J, Altieri C, Russell P. The effects of hamstring stretching on range of motion: a systematic literature review. *J Orthop Sports Phys Ther*. 2005;35(6):377–87.
80. Radford JA, Burns J, Buchbinder R, Landorf KB, Cook C. Does stretching increase ankle dorsiflexion range of motion? A systematic review. *Br J Sports Med*. 2006;40(10):870–5.
81. Trajano GS, Nosaka K, Blazevich AJ. Neurophysiological mechanisms underpinning stretch-induced force loss. *Sports Med*. 2017;47(8):1531–41.
82. Behm DG, Alizadeh S, Daneshjoo A, Hadjizadeh Anvar S, Graham A, Zahiri A, Goudini R, Edwards C, Culleton R, Scharf C, Konrad A. Acute effects of various stretching techniques on range of motion: A systematic review with meta-analysis. *Sports Medicine*. 2023; in press.
83. Etnyre BR, Lee EJ. Chronic and acute flexibility of men and women using 3 different stretching techniques. *Res Quart Exerc Sport*. 1988;59(3):222–8.
84. Ferber R, Osternig L, Gravelle D. Effect of PNF stretch techniques on knee flexor muscle EMG activity in older adults. *J Electromyogr Kinesiol*. 2002;12(5):391–7.
85. O'Hara J, Cartwright A, Wade CD, Hough AD, Shum GL. Efficacy of static stretching and proprioceptive neuromuscular facilitation stretch on hamstrings length after a single session. *J Strength Cond Res*. 2011;25(6):1586–91.
86. Maddigan ME, Peach AA, Behm DG. A comparison of assisted and unassisted proprioceptive neuromuscular facilitation techniques and static stretching. *J Strength Cond Res*. 2012;26(5):1238–44.
87. Condon SM, Hutton RS. Soleus muscle electromyographic activity and ankle dorsiflexion range of motion during four stretching procedures. *Phys Ther*. 1987;67(1):24–30.
88. Johnson AW, Mitchell UH, Meek K, Feland JB. Hamstring flexibility increases the same with 3 or 9 repetitions of stretching held for a total time of 90 s. *Phys Ther Sport*. 2014;15(2):101–5.
89. Bandy WD, Irion JM, Briggler M. The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Phys Ther*. 1997;77:1090–6.
90. Cipriani D, Abel B, Pirwitz D. A comparison of two stretching protocols on hip range of motion: Implications for total daily stretch duration. *J Strength Cond Res*. 2003;17(2):274–8.



91. Hatano G, Matsuo S, Asai Y, Suzuki S, Iwata M. Effects of high-intensity stretch with moderate pain and maximal intensity stretch without pain on flexibility. *J Sports Sci Med*. 2022;21(2):171–81.
92. Donti O, Gaspari V, Papia K, Panidi I, Donti A, Bogdanis GC. Acute effects of intermittent and continuous static stretching on hip flexion angle in athletes with varying flexibility training background. *Sports (Basel)*. 2020;3(8):3.
93. Aguilar AJ, DiStefano LJ, Brown CN, Herman DC, Guskiewicz KM, Padua DA. A dynamic warm-up model increases quadriceps strength and hamstring flexibility. *J Strength Cond Res*. 2012;26(4):1130–41.
94. Azevedo DC, Melo RM, Alves Correa RV, Chalmers G. Uninvolved versus target muscle contraction during contract: relax proprioceptive neuromuscular facilitation stretching. *Phys Ther Sport*. 2011;12(3):117–21.
95. Barbosa GM, Figueiredo Dantas GA, Rodrigues Silva B, Oliveira Souza T, Herickson Brito Vieira W. Static or dynamic stretching program does not change the acute responses of neuromuscular and functional performance in healthy subjects: a single blind randomized controlled trial. *Revista Brasileira de Ciencias do Esporte*. 2018;40(4):418–26.
96. Cesar EPKdS T, Soares de Resende C, Rezendo YGM. The role of static stretching on performance variables and induced effects of exhaustion exercises in Brazilian jiu-jitsu athletes. *Archives of Budo / Sci Martial Arts*. 2016;12:211–8.
97. Chatzopoulos DK, Doganis G, Messaritakis V, Lykesas G. Effects of varying volumes of dynamic stretching on active range of motion, reaction time, and movement time in female soccer players. *J Exerc Physiol online*. 2019;22(5):147–56.
98. Chen CH, Huang TS, Chai HM, Jan MH, Lin JJ. Two stretching treatments for the hamstrings: proprioceptive neuromuscular facilitation versus kinesio taping. *J Sport Rehabil*. 2013;22(1):59–66.
99. Lo CL, Hsueh YH, Wang CH, Chang HY. Comparison of the acute effects of kinesio taping and sleeper stretching on the shoulder rotation range of motion, manual muscle strength, and sub-acromial space in pitchers with glenohumeral internal rotation Deficit. *Medicina (Kaunas)*. 2021;23:57(2).
100. Karagozoglu Coskunsu DM, E.K.; Ozdinciler, A.R. Proprioceptive neuromuscular facilitation stretching combined with Kinesio taping for hamstring flexibility in amateur athletes: a single-blind, randomized, controlled trial. *Physio Quarterly*. 2021;29(3):56–61.
101. Depino GM, Webright WG, Arnold BL. Duration of maintained hamstring flexibility after cessation of an acute static stretching protocol. *J Athl Train*. 2000;35(1):56–9.
102. Espejo-Antunez LL-M, P.A.; Alborno-Cabello, M.; Garrido-Ardilla, E.M. Acute effect of electrical muscle elongation and static stretching in hamstring muscle extensibility. *Sci Sports*. 2016;31:1–7.
103. Hammer AM, Hammer RL, Lomond KV, O'Connor P. Acute changes of hip joint range of motion using selected clinical stretching procedures: a randomized crossover study. *Musculoskelet Sci Pract*. 2017;32:70–7.
104. Hanney WJ, Puente-dura EJ, Kolber MJ, Liu X, Pabian PS, Cheatham SW. The immediate effects of manual stretching and cervicotheracic junction manipulation on cervical range of motion and upper trapezius pressure pain thresholds. *J Back Musculoskelet Rehabil*. 2017;30(5):1005–13.
105. Ikeda N, Ryushi T. Effects of 6-week static stretching of knee extensors on flexibility, muscle strength, jump performance, and muscle endurance. *J Strength Cond Res*. 2021;35(3):715–23.
106. Kaneda HN, T.; Kouji, T.; Kiyoshi, T.; Kenta, S.; Sho, K.; Yoshiki, T.; Shuichi, S.; Kensuke, F.; Tomonori, K. The effects of tissue flossing and static stretching on gastrocnemius exertion and flexibility. *Isokinetics Exerc Sci*. 2020;28(2):205–13.
107. Konrad A, Reiner MM, Thaller S, Tilp M. The time course of muscle-tendon properties and function responses of a five-minute static stretching exercise. *Eur J Sport Sci*. 2019;19(9):1195–203.
108. Kuruma HT, Nitta O, Furukawa Y, Shida N, Kamio H, Yanagisawa K. Effects of myofascial release and stretching technique on range of motion and reaction time. *J Phys Ther Sci*. 2013;25(2):169–71.
109. Lim KI, Nam HC, Jung KS. Effects on hamstring muscle extensibility, muscle activity, and balance of different stretching techniques. *J Phys Ther Sci*. 2014;26(2):209–13.
110. Maeda MU, Fujii E, Moriyama N, Iwata S, Sasada J. The effect of different stretching techniques on ankle joint range of motion and dynamic postural stability after landing. *J Sports Med Phys Fitness*. 2016;56:692–8.
111. Maeda N, Urabe Y, Tsutsumi S, Sakai S, Fujishita H, Kobayashi T, et al. The acute effects of static and cyclic stretching on muscle stiffness and hardness of medial gastrocnemius muscle. *J Sports Sci Med*. 2017;16(4):514–20.
112. Maeda MK, S.; Urabe, Y.; Sasada, J.; Morikawa, M.; Nishikawa, Y.; Acute effects of local vibration stretching on ankle range of motion, vertical jump performance and dynamic balance after landing. *Isokinetics Exerc Sci*. 2020;29(1).
113. Melo MS, Barbosa GM, Laurentino, ALBA, Franca IM, Souza TO, Brito Vieira W.H. Static stretching at pain-tolerated intensity is not necessary to increase knee range of motion in amateur soccer players: a randomized trial. *Muscles Ligaments and Tendons J*. 2021;11(3): 536–46.
114. Michaeli A, Tee JC, Stewart A. Dynamic oscillatory stretching efficacy on hamstring extensibility and stretch tolerance: a randomized controlled trial. *Int J Sports Phys Ther*. 2017;12(3):305–13.
115. Nishikawa Y, Aizawa J, Kanemura N, Takahashi T, Hosomi N, Maruyama H, et al. Immediate effect of passive and active stretching on hamstrings flexibility: a single-blinded randomized control trial. *J Phys Ther Sci*. 2015;27(10):3167–70.
116. Pepper TM, Brismee JM, Sizer PS Jr, Kapila J, Seeber GH, Huggins CA, et al. The immediate effects of foam rolling and stretching on iliotibial band stiffness: a randomized controlled trial. *Int J Sports Phys Ther*. 2021;16(3):651–61.
117. Pollard H, Ward G. A study of two stretching techniques for improving hip flexion range of motion. *J Manipulative Physiol Ther*. 1997;20(7):443–7.
118. Pratt KB. Effects of a 3-minute standing stretch on ankle-dorsiflexion range of motion. *J Sport Rehabil*. 2003;12(2):162–73.
119. Rodrigues SAR, A.S.; Couto, B.P.; Motta-Santos, D.; Drummond, M.D.M.; Goncalves, R.; Silva, R.A.D.; Szmuchowski, L.A. . Acute effects of single bout of stretching exercise and mechanical vibration in hamstring muscle. *J Exerc Physiol* 2017;20:46–57.
120. Rowlett CA, Hanney WJ, Pabian PS, McArthur JH, Rothschild CE, Kolber MJ. Efficacy of instrument-assisted soft tissue mobilization in comparison to gastrocnemius-soleus stretching for dorsiflexion range of motion: a randomized controlled trial. *J Bodyw Mov Ther*. 2019;23(2):233–40.
121. Rubini EC, Souza AC, Mello ML, Bacurau RF, Cabral LF, Farinatti PT. Immediate effect of static and proprioceptive neuromuscular facilitation stretching on hip adductor flexibility in female ballet dancers. *J Dance Med Sci*. 2011;15(4):177–81.
122. Rubley MB, J.B.; Knight, K.L.; Ricard, M.; Draper, D.; Flexibility retention 3 Weeks after a 5-Day training regime. *J Sport Rehabil*. 2001;10(2):105–12.
123. Ryan ED, Everett KL, Smith DB, Pollner C, Thompson BJ, Sobolewski EJ, et al. Acute effects of different volumes of dynamic stretching on vertical jump performance, flexibility and muscular endurance. *Clin Physiol Funct Imaging*. 2014;34(6):485–92.
124. Schuback BH, Salisbury LA. A comparison of a self-stretch incorporating proprioceptive neuromuscular facilitation components and a therapist-applied PNF-technique on hamstring flexibility. *Physiotherapy*. 2004;90(3):151–7.
125. Silva SBd EM, Almeida JB, Bernardes RC, Valenti VE, Vanderlei LCM, de Abreu LC. Effects of two proprioceptive neuromuscular facilitation techniques in different planes on hamstrings muscles of healthy subjects. *HealthMed*. 2012;7:2332–8.
126. Smith JC, Pridgeon B, Hall MC. Acute effect of foam rolling and dynamic stretching on flexibility and jump height. *J Strength Cond Res*. 2018;32(8):2209–15.
127. Spennoga SG, Uhl TL, Arnold BL, Gansneder BM. Duration of maintained hamstring flexibility after a one-time, modified hold-relax stretching protocol. *J Athl Train*. 2001;36(1):44–8.
128. Vernetta-Santana MA-V, L.; Robles-Fuentes, A.; Lopez-Bedoya, J. Acute effect of active isolated stretching technique on range of motion and peak isometric force. *J Sports Med Phys Fitness*. 2015;55(11):1299–309.
129. Viveiros LP, M.D.; Simao, R.; Farinatti, P.; Immediate and late acute responses of flexibility in the shoulder extension in relation to the

- number of series and stretching duration. *Revista Brasileira Medicina Esporte*. 2004;10(6):464–7.
130. de Weijer VC, Gorniak GC, Shamus E. The effect of static stretch and warm-up exercise on hamstring length over the course of 24 hours. *J Orthop Sports Phys Ther*. 2003;33(12):727–33.
  131. Wiemann K, Hahn K. Influences of strength, stretching and circulatory exercises on flexibility parameters of the human hamstrings. *Int J Sports Med*. 1997;18(5):340–6.
  132. Yildiz S, Gelen E, Cilli M, Karaca H, Kayihan G, Ozkan A, et al. Acute effects of static stretching and massage on flexibility and jumping performance. *J Musculoskelet Neuronal Interact*. 2020;20(4):498–504.
  133. Zakas A, Vergou A, Grammatikopoulou MG, Zakas N, Sentelidis T, Vamvakoudis S. The effect of stretching during warming-up on the flexibility of junior handball players. *J Sports Med Phys Fitness*. 2003;43(2):145–9.
  134. Zito M, Driver D, Parker C, Bohannon R. Lasting effects of one bout of two 15-second passive stretches on ankle dorsiflexion range of motion. *J Orthop Sports Phys Ther*. 1997;26(4):214–21.

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