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Review

Does pre-exercise static stretching inhibit maximal muscular performance? A meta-analytical review

L. Simic[1], N. Sarabon[2], G. Markovic[1]

[1]Motor Control and Human Performance Laboratory, School of Kinesiology, University of Zagreb, Zagreb, Croatia, [2]Institute for Kinesiology Research, University of Primorska, Science and Research Center, Koper, Slovenia
Corresponding author: Goran Markovic, Motor Control and Human Performance Laboratory, School of Kinesiology, University of Zagreb, Horvacanski zavoj 15, 10000 Zagreb, Croatia. Tel: +385 1 3658 606, Fax: +385 1 3634 146, E-mail: gmarkov@kif.hr

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We applied a meta-analytical approach to derive a robust estimate of the acute effects of pre-exercise static stretching (SS) on strength, power, and explosive muscular performance. A computerized search of articles published between 1966 and December 2010 was performed using PubMed, SCOPUS, and Web of Science databases. A total of 104 studies yielding 61 data points for strength, 12 data points for power, and 57 data points for explosive performance met our inclusion criteria. The pooled estimate of the acute effects of SS on strength, power, and explosive performance, expressed in standardized units as well as in percentages, were –0.10 [95% confidence interval (CI): –0.15 to –0.04], –0.04 (95% CI: –0.16 to 0.08), and –0.03 (95% CI: –0.07 to 0.01), or –5.4% (95% CI: –6.6% to –4.2%), –1.9% (95% CI: –4.0% to 0.2%), and –2.0% (95% CI: –2.8% to –1.3%). These effects were not related to subject's age, gender, or fitness level; however, they were more pronounced in isometric vs dynamic tests, and were related to the total duration of stretch, with the smallest negative acute effects being observed with stretch duration of ≤45 s. We conclude that the usage of SS as the sole activity during warm-up routine should generally be avoided.

Static stretching (SS) is commonly performed prior to exercise (ACSM, 2000) and athletic events (Beaulieu, 1981; Holcomb, 2000). It is generally believed that pre-exercise SS will promote better performances and reduce the risk of injury during exercise (Shellock & Prentice, 1985; Smith, 1994). However, recent reviews have suggested that pre-exercise SS might reduce the incidence of some (e.g., muscle strains) (McHugh & Cosgrave, 2010), but not all injuries (Herbert & Gabriel, 2002; Thacker et al., 2004), and that it may actually reduce performance (Shrier, 2004; Rubini et al., 2007; McHugh & Cosgrave, 2010; Behm & Chaouachi, 2011). More importantly, stretch-induced reductions in performance are particularly evident in maximal and explosive muscular efforts that play an essential role in a number of individual and team sports (Markovic & Mikulic, 2010; Cormie et al., 2011). These results have already made an impact on sports and exercise professionals who now start to recommend avoidance of SS during warm-up for sport and exercise (Pearson, 2001; Young & Behm, 2002; Knudson, 2007).

Despite an increasing number of studies that demonstrated an acute reduction in muscular performance following SS (for recent reviews, see Magnusson & Renstrom, 2006; Rubini et al., 2007; McHugh & Cosgrave, 2010; Behm & Chaouachi, 2011), it has to be acknowledged that many studies reported no reduction in strength, power, or explosive muscular performance following SS (Bazett-Jones et al., 2005; Burkett et al., 2005; Cramer et al., 2005, 2007b; Unick et al., 2005; Little & Williams, 2006; McMillian et al., 2006; O'Connor et al., 2006; Maisetti et al., 2007; Kinser et al., 2008; Torres et al., 2008; Wallmann et al., 2008; Di Cagno et al., 2010; Haag et al., 2010; Handrakis et al., 2010; Molacek et al., 2010; Murphy et al., 2010), while some of them even reported improvement in performance (O'Connor et al., 2006; Gonzalez-Rave et al., 2009; Haag et al., 2010). Moreover, we still do not know a precise magnitude of stretch-induced acute changes in muscular performance. Finally, the total duration of muscle stretching in most studies in this area was much longer than the ranges normally used in practice and recommended in literature, i.e., 15–30 s per muscle group (Rubini et al., 2007; Young, 2007). Given the widespread use of SS in exercise and rehabilitation settings, it is of both scientific and practical relevance to determine a precise estimate of acute effects of SS on muscle function and exercise performance.

While two narrative reviews (McHugh & Cosgrave, 2010; Behm & Chaouachi, 2011) and one systematic review (Kay & Blazevich, 2011) have been recently published on this topic and reported average effects of acute

SS on various performance measures, none of those studies actually used an appropriate statistical tool for combining and analyzing individual study findings in a quantitative manner. Thus, the precise magnitude of stretch-induced acute changes in muscular performance is still unknown. In the present study, we applied a meta-analytical approach to derive a robust estimate of the acute effects of SS on muscle strength, power, and explosive muscular performance. We also seek to understand whether these effects (a) were specific with respect to the subject characteristics (age, gender, and training status) and type of performance test, and (b) depend on the total duration of SS per muscle group.

Methods

Literature search and study selection

Searches of PubMed, SCOPUS, and Web of Science were performed for studies published in English up to and including December 2010. We used the following search phase (static stretch OR static stretching OR acute stretch OR acute stretching OR passive stretch OR warm-up) AND (strength OR force OR torque OR jump OR sprint OR throw OR performance). Reference lists in review and original research articles identified were also examined. The present meta-analysis includes studies published in journals that have presented original research data on healthy human subjects. No age or gender restrictions were imposed at the search stage. Abstracts and unpublished theses/dissertations were excluded from this analysis due to lack of methodological details. Inclusion criteria applied in this study were as follows: (a) crossover, randomized, and non-randomized control trials; (b) studies that evaluated acute effects of SS on human muscular strength, power, and explosive muscular performance; (c) studies in which SS lasted not longer than 30 min; and (d) English language studies published in peer-reviewed journals. Our search strategy retrieved 1168 hits in PubMed, 285 hits in SCOPUS, and 216 hits in Web of Science. Studies that examined the acute effects of SS on other fitness qualities (e.g., muscular or cardiorespiratory endurance, flexibility, agility, balance, repeated-sprint ability, etc.; Zakas et al., 2003, 2006c, e; Knudson et al., 2004; Young et al., 2004; Nelson et al., 2005b; Beckett et al., 2009; Sim et al., 2009; Costa et al., 2009a; Amiri-Khorasani et al., 2010; Covert et al., 2010; Samogin Lopes et al., 2010; Wilson et al., 2010) were not included in this meta-analytical review. Also, due to significant contralateral effect of acute SS (Cramer et al., 2005), studies that used the contralateral (unstretched) limb as a control were not considered in this meta-analytical review. A total of 115 articles that studied the acute effects of SS (either active or passive) on maximal muscle strength [one repetition maximum (1 RM), isometric or isokinetic force or torque], muscle power, and explosive muscular performance [rate of force or torque development (RFD), jumping, sprinting, and throwing performance] was identified. Note that we excluded from this list several potentially relevant studies on the grounds of having no control (i.e., prestretch) condition (Faigenbaum et al., 2005, 2006a, b; Thompsen et al., 2007; Taylor et al., 2009). Furthermore, some studies were excluded as they combined SS with dynamic stretching (Fletcher & Anness, 2007; Sim et al., 2009; Taylor et al., 2009). Finally, some studies were excluded because SS lasted more than 30 min (Avela et al., 1999, 2004), or because they combined stretching and maximal voluntary contractions (Kay & Blazevich, 2009a, 2010). Note also that numerous studies met our inclusion criteria but failed to report all or some of the results in numerical format (Kokkonen et al., 1998; Fowles et al., 2000; Behm et al., 2001, 2004, 2006; Cornwell et al., 2001, 2002; Nelson et al. 2001a, b; Siatras et al., 2003, 2008; Power et al., 2004; Papadopoulos et al., 2005; Knudson & Noffal, 2005; Wallmann et al., 2005, 2008; Little & Williams, 2006; O'Connor et al., 2006; Behm & Kibele, 2007; Ogura et al., 2007; Bradley et al., 2007; Maisetti et al., 2007; Herda et al., 2008, 2009, 2010; Holt & Lambourne, 2008; Samuel et al., 2008; Bacurau et al., 2009; Hough et al., 2009; Kay & Blazevich, 2009a; Pearce et al., 2009). In these cases, a personal contact was made with the authors to retrieve appropriate information. However, several authors did not respond to our request; therefore, we manually calculated the results from the figures (in combination with data from articles). Only one study was partly excluded (i.e., for one primary outcome) for poor reporting of data (Winke et al., 2010). Thus, altogether, 104 studies met our inclusion criteria and were included in this meta-analytical review.

Assessment of study quality

Methodological quality was assessed with the PEDro scale (Maher et al., 2003). The quality of the included studies was assessed independently by two assessors, and disagreements were resolved by a third independent assessor.

Coding and classifying variables

Each study that met our inclusion criteria was recorded on a coding sheet. The major categories coded included (a) study characteristics; (b) subject characteristics; (c) intervention characteristics; and (d) primary outcome characteristics. The study characteristics that were coded included author(s) name, journal, year of publication, and the number of subjects. Subject characteristics that were coded included age, gender, and fitness level. Gender was coded as a variable representing the proportion of men in the sample (e.g., 1 for all men; 0.5 for five women and five men; and 0 for all women). Fitness level was coded as "non-athletes" (physically inactive persons and recreationally trained individuals) and "athletes" (competitive level). Intervention characteristics that were coded included stretched muscles and total duration of stretching per muscle group per limb. Note that in several cases, the total duration of SS per muscle group per limb was not explicitly defined; in these cases, we calculated it from the available data (i.e., total duration of SS, number of sets, and/or exercises). Furthermore, in several cases, researchers applied different number of stretching exercises per selected muscle groups. This resulted in large variation in mean duration of SS per muscle group. In these cases, we reported mean duration of SS of primary muscle group(s) (with respect to primary outcome), together with the respective range of duration of SS per muscle group per limb. Finally, primary outcome characteristics that were coded included type of exercise test applied for the assessment of maximal muscle strength (1RM, isometric peak force/torque, or isokinetic peak torque), muscle power (mean or peak power), and explosive muscular performance (RFD, jumping, sprinting, or throwing performance). Note that many of the included studies applied a one-group repeated-measure design (i.e., no stretch and SS condition). Although it is possible to perform a meta-analysis on studies that applied different study designs (i.e., independent groups vs matched groups; Borenstein et al., 2009), we decided to treat each study included in this meta-analysis as a one-group pre-/posttest intervention (Peterson et al., 2010). Therefore, coding of performance change was only carried out for groups receiving the SS treatment. Specifically, for all studies, means and standard deviation (SD) for pre- and poststretching condition were extracted. In cases where the author(s) measured >1 poststretching condition (i.e., time course of changes in performance after static stretching; e.g., Fowles et al., 2000; Brandenburg et al., 2007), only the first poststretching condition was considered.

Data extraction and data analyses

Given that each treatment group was considered a one-group pre-/posttest intervention, the study estimate for the acute effect of SS on muscle strength, muscle power, and explosive muscular performance is given by the difference between the post- and pre-stretching results in primary outcomes divided by a within-group SD (SD_{within}; Borenstein et al., 2009), i.e., the standardized mean difference *d*. The within-group SD (SD_{within}) was obtained using the following formula:

$$SD_{\text{within}} = \frac{S_{\text{diff}}}{\sqrt{2 \times (1-r)}}$$

where S_{diff} is the standard deviation of the difference scores and *r* is the correlation between pairs of observation (i.e., the pretest–posttest correlation of performance measures). Note that many of the studies did not report S_{diff}. Rather, the majority of studies obtained for this analysis included the SDs for the pre- and post-stretching performance outcomes, or sometimes the standard errors of the mean. For all other studies, S_{diff} was calculated using the pre- and poststretching SDs, as well as pretest–posttest correlation of performance measures *r* using the following equation (Follmann et al., 1992; Peterson et al., 2010):

$$SD_{\text{diff}} = \sqrt{\left[SD_{\text{pre}}{}^2 + SD_{\text{post}}{}^2 - 2 \times r \times SD_{\text{pre}} \times SD_{\text{post}}\right]}$$

For the purpose of this meta-analysis, pretest–posttest correlation of performance measures r was 0.9. Note that changing r to 0.8 or to 0.7 had a little effect on pooled estimates and would not change the main conclusion of this meta-analytical review. The standard error (SEd) of d is given by (Borenstein et al., 2009):

$$SE_d = \sqrt{\left(\frac{1}{n} + \frac{d^2}{2 \times n}\right) \times 2 \times (r-1)}$$

where *n* is the number of pairs.

We also expressed the study estimates relative to the pre-stretching mean value, that is, in percentage values. Percentage effects were converted to factors (= 1 + effect/100), log transformed for the analysis, and then back transformed to percentages (Bonetti & Hopkins, 2009). In this case, the standard error (SE_d) of *d* was approximated by the following equation (Peterson et al., 2010):

$$SE_d = \frac{R \times \sqrt{\left[CV_{\text{pre}}{}^2 + CV_{\text{post}}{}^2 - 2 \times r \times CV_{\text{pre}} \times CV_{\text{post}}\right]}}{\sqrt{n}}$$

where *R* represents the ratio of post- and prestretch performance measures, *CV* denotes the coefficient of variation equaling the ratio of *SD* and mean at the respective time (i.e., pre- and post-stretching), *r* is pretest–posttest correlation of performance measures, and *n* represents the number of participants.

A random-effects model was chosen for meta-analysis to account for heterogeneity in effect *d* among trials. The weight factor by which the study estimates were weighted was

$$\frac{1}{SE_d{}^2 + \tau^2}$$

where τ is the between-study variation (Borenstein et al., 2009). Separate meta-analyses were performed for maximum muscle strength (peak isometric force or torque, 1RM, concentric or eccentric isokinetic peak torque), muscle power (mean and peak power), and explosive muscular performance (RFD, jumping performance, sprinting performance, and throwing performance). Furthermore, within the maximal muscle strength and explosive muscular performance category, separate meta-analyses were performed for isometric vs dynamic maximal strength, and for rate of force/torque development vs jumping performance (vertical jump height and horizontal jump distance) vs sprinting performance (sprint velocity or sprint time over distances between 5 and 100 m) vs throwing performance (throwing velocity or throwing distance). Note that a number of studies reported >1 primary outcome owing to >1 performance test measured. In cases where multiple outcomes belonged to the same performance category being meta-analyzed, we computed the composite effect and the respective *SE* according to Borenstein et al. (2009). For all pooled estimates, we calculated the 95% confidence intervals (95% CI), and we made probabilistic magnitude-based inferences about the true values of the effects, as suggested by Hopkins and co-workers (Batterham & Hopkins, 2006; Bonetti & Hopkins, 2009; Hopkins et al., 2009). An effect was deemed unclear if its 95% CI overlapped the thresholds for smallest positive and negative effects; equivalently, the effect was unclear if chances of the true value being substantially positive and negative were both >5% (Batterham & Hopkins, 2006). The probabilities for each meta-analyzed effect were derived using a published spreadsheet (Hopkins, 2007). An estimate of the smallest substantial change in performance is required to make these inferences. Based on variability in competitive athletic performance reported by Hopkins and co-workers (Hopkins, 2004, 2005; Bonetti & Hopkins, 2010; Smith & Hopkins, 2011), we defined the threshold change in performance for benefit and harm for field-based explosive performance tests (i.e., jumping, sprinting, and throwing performance) and muscle power as 1%. For strength performance [i.e., maximal muscle strength and RFD], the corresponding threshold change were derived from the within-individual variability in strength performance, expressed as coefficient of variation. The within-individual variation in muscle strength and RFD varies considerably due to the well-known factors like type of test, type and velocity of contraction, muscle group being tested, subject's characteristics, etc. (Abernethy et al., 1995; Wilson & Murphy, 1996). However, it usually ranges between 3% and 15%. If we conservatively take 3% as a typical within-individual variation in strength performance, we may approximate the smallest substantial change by multiplying this value with the factor of 1.5 or 2 (Hopkins, 2000). We therefore defined this threshold change as 5%.

Heterogeneity of effects for each meta-analysis was assessed using the quantity I^2, as suggested by Higgins and co-workers (Higgins et al., 2003). In brief, I^2 was calculated as follows: $I^2 = 100\% \cdot (Q - \text{d.f.})/Q$, where *Q* is Cochran's χ^2 heterogeneity statistic and d.f. is the degrees of freedom. The Cochran's *Q* is calculated by summing the squared deviations of each trial's estimate from the overall meta-analytical estimate. I^2 describes the percentage of variability in point estimates which is due to heterogeneity rather than sampling error. I^2 values of 25%, 50%, and 75% represent low, moderate, and high statistical heterogeneity, respectively (Higgins et al., 2003).

Publication bias, as well as evidence of outliers, was examined by funnel plots of standard errors of the estimate of the acute effect vs calculated study estimates *d*. In addition, publication bias was also statistically evaluated by calculating rank correlations between effect estimates and their standard errors (i.e., Kendall's τ statistic; Begg & Mazumdar, 1994). A significant result was considered to be suggestive of publication bias.

Subgroup analyses for each primary outcome included subject's training status (athletes vs non-athletes), SS categories formed according to stretch duration per muscle (≤45 s vs 46 s to 90 s vs >90 s), and type of muscular performance test (isometric vs dynamic test for maximal muscle strength; RFD vs jumping performance vs sprinting performance vs throwing performance for explosive muscular performance), and were performed using a *Q*-test based on analysis of variance (Borenstein et al., 2009). In cases where the total duration of stretching was different among stretched muscle groups, the average stretch duration was used in further analyses. Similarly, for studies that reported acute effects of SS of different durations on a particular primary outcome (e.g., Zakas et al. 2006a; Zakas et al. 2006b; Zakas et al. 2006d; Ogura et al., 2007; Kay & Blazevich, 2008; Ryan et al. 2008b; Winchester et al., 2009), along with calculation of the composite effect (see previous text), we averaged the total duration of stretching per muscle group. Meta-regression was used for analyzing the relationship between study estimates and the selected subject or training characteristics: subject's age, gender, and total duration of stretching per muscle (Borenstein et al., 2009). The level of significance was set to $P < 0.05$.

Results

Descriptive statistics

Altogether, 104 published investigations were included in the meta-analyses, giving 61 study estimates for maximal muscle strength, 12 study estimates for muscle power, and 57 study estimates for explosive muscular performance. Tables 1–3 summarize the characteristics of the included studies. Altogether, 962 subjects (593 males and 369 females) were included in the meta-analysis of maximal muscle strength, 195 subjects (125 males and 70 females) were included in the meta-analysis of muscle power, and 1072 subjects (719 males and 353 females) were included in the meta-analysis of explosive muscular performance. The average duration of pre-exercise SS per muscle group per limb for maximal muscle strength, muscle power, and explosive muscular performance tests was 314, 255, and 86 s, respectively.

Methodological quality of included studies

The range of quality scores was 2–5 (median 4) out of 10. Often a report did not clearly specify that a criterion was met, and, consequently, we scored the study as not satisfying the criterion. Note that all studies failed to satisfy the following five methodological criteria: treatment allocation concealment, blinding of all subjects, blinding of all therapists, blinding of all assessors, and intention to treat analyses (i.e., items 3, 5, 6, 7, and 9, respectively).

Primary outcomes

Tables 1–3 report individual changes in the primary outcomes and summarize the pooled estimates of the acute effects of SS on maximal muscle strength, muscle power, and explosive muscular performance.

Maximal muscle strength

For the maximal muscle strength (i.e., peak force, torque, or 1RM), pooled estimate of the acute effect of SS, expressed in standardized units, was $d = -0.10$ (95% CI: –0.15 to –0.04). When expressed in percentages, the respective pooled estimate was –5.4% (95% CI: –6.6% to –4.2%), indicating a likely negative acute effect. The statistical heterogeneity of the acute effect of SS on muscle strength was low ($I^2 = 5\%$). The inspection of the funnel plot as well as Kendall's τ statistic ($r = -0.11$; $P = 0.20$) suggests no presence of publication bias in maximal muscle strength tests. Notably, one study could be defined as outlying (Behm et al., 2001); however, its exclusion from the meta-analysis did not affect the pooled estimate. Subgroup analyses showed similar acute effect of SS on maximal muscle strength in both athletes and non-athletes ($P = 0.97$). With respect to the type of test applied, significantly larger ($P = 0.012$) pooled negative acute effect of SS was observed for isometric vs dynamic strength tests (Fig. 1(a)), although the average stretch duration per muscle group did not differ significantly between the two groups of tests (333 s vs 290 s; $P > 0.05$). Specifically, pooled estimates for the acute effect of SS on isometric and dynamic strength tests were –6.5% (95% CI: –8.3% to –4.6%; almost certainly negative effect) and –3.9% (95% CI: –4.8% to –2.9%; most likely trivial effect), respectively. With respect to the stretch duration, we observed a trend ($P = 0.18$) toward diminishing the negative acute effect of SS on maximal muscle strength with shorter stretch duration (Fig. 2(a)). In particular, pooled estimates for the acute effect of SS lasting ≤45 s, 46–90 s, and >90 s per muscle group on maximal muscle strength were –3.2% (95% CI: –5.6% to –0.8%; most likely trivial effect), –5.6% (95% CI: –7.3% to –3.8%; likely negative effect), and –6.1% (95% CI: –7.9% to –4.3%; almost certainly negative effect), respectively.

Muscle power

Pooled estimate of the acute effect of SS on muscle power was $d = -0.04$ (95% CI: –0.16 to 0.08). When expressed in percentages, the respective pooled estimate was –1.9% (95% CI: –4.0% to 0.2%), indicating an unclear acute effect of SS on muscle power. We also observed very low heterogeneity of acute effects of SS on muscle power ($I^2 = 3.6\%$). Note also that both funnel plot and Kendall's τ statistic ($r = -0.36$; $P = 0.09$) showed no evidence of publication bias in muscle power tests. Subgroup analyses showed similar acute effect of SS on muscle power in both athletes and non-athletes ($P = 0.7$). Although limited by the number of studies, subgroup analysis related to stretch duration showed a trend ($P = 0.10$) toward reduction of the negative acute effect of SS on muscle power with shorter stretch duration (Fig. 2(b)). Specifically, pooled estimates for the acute effect of SS lasting ≤45, 46–90, and >90 s per muscle group on muscle power were 0.4% (95% CI: –5.8% to 6.6%; an unclear effect), –1.7% (95% CI: –5.1% to 1.6%; possibly negative effect), and –3.3% (95% CI: –7.2% to 0.6%; a likely negative effect), respectively.

Table 1. Summary of the investigations included in the meta-analyses of acute effects of static stretching on maximal muscle strength

Study	Age (years)	Fitness level	Sample size M/F	Duration of stretch (s)	Stretched muscle groups	Performance measure	Effect size (SE)	95% CI	% change (SE)	95% CI
Allison et al. (2008)	25	A	10/0	240 (240–360)	PF, KE, KF, HF	F	–0.25 (0.28)	–0.80 to 0.30	–5.7 (3.1)	–11.8 to 0.4
Babault et al. (2010)	23	N-A	10/0	600	PF	T	–0.56 (0.57)	–1.69 to 0.57	–10.1 (2.5)	–15.0 to –5.2
Bacurau et al. (2009)	23.1	N-A	0/14	270	KE,KF	1RM	–0.78 (0.94)	–2.62 to 1.06	–13.4 (1.8)	–16.9 to –9.9
Bazett-Jones et al. (2005)	20.6	A	10/0	90	KE, KF, HE, HF	F	0.05 (0.14)	–0.23 to 0.33	0.9 (2.8)	–4.6 to 6.5
Beedle et al. (2008)*	20.4	N-A	19/0	45	KE, KF, UB	F	–0.05 (0.14)	–0.33 to 0.23	–1.2 (2.3)	–5.7 to 3.3
Beedle et al. (2008)*	20.4	N-A	0/32	45	KE, KF, UB	F	–0.05 (0.14)	–0.33 to 0.23	–0.8 (1.3)	–3.3 to 1.8
Behm et al. (2006)*	25	N-A	9/9	90	PF, KE, KF	F	–0.16 (0.24)	–0.64 to 0.32	–6.5 (3.9)	–14.1 to 1.1
Behm et al. (2006)	21.9	N-A	12/0	90	PF, KE, KF	F	–0.36 (0.42)	–1.19 to 0.47	–7.4 (3.7)	–14.7 to –0.2
Behm et al. (2004)	24.1	N-A	16/0	135 (135–270)	PF, KE, KF	F	–0.41 (0.53)	–1.45 to 0.63	–6.9 (1.9)	–10.7 to –3.1
Behm et al. (2001)	N/A	N-A	18/0	900	KE	F	–2.36 (3.17)	–8.58 to 3.86	–12.2 (0.5)	–13.2 to –11.2
Brandenburg (2006)	23.4	N-A	10/6	135 (90–180)	KF	F	–0.27 (0.35)	–0.95 to 0.41	–6.2 (2.5)	–11.1 to –1.3
Brandenburg (2006)	23.4	N-A	10/6	135 (90–180)	KF	T (120°/s)	–0.17 (0.17)	–0.51 to 0.17	–4.3 (2.2)	–8.6 to –0.1
Costa et al. (2009c)*	20.8	N-A	0/13	480	PF,KF	T (60/180/300°/s)	–0.19 (0.20)	–0.58 to 0.20	–6.9 (3.5)	–13.9 to 0.0
Costa et al. (2009b)*	22	N-A	15/0	480	PF, KF	T (60/180/300°/s)	–0.03 (0.10)	–0.23 to 0.17	–0.7 (2.1)	–4.7 to 3.4
Cramer et al. (2007a)*	22	N-A	15/0	480	KE	T (60/240°/s)	–0.14 (0.20)	–0.53 to 0.25	–2.4 (1.9)	–6.2 to 1.5
Cramer et al. (2005)*	20.8	N-A	7/14	480	KE	T (60/180°/s)	–0.11 (0.17)	–0.45 to 0.23	–3.8 (3.9)	–11.5 to 3.9
Cramer et al. (2004)*	21.4	N-A	0/14	480	KE	T (60/300°/s)	–0.12 (0.20)	–0.51 to 0.27	–3.6 (1.0)	–5.5 to –1.6
Cramer et al. (2006)*	23	N-A	0/13	480	KE	T (60/300°/s)	–0.95 (0.94)	–2.79 to 0.89	–2.5 (1.5)	–5.4 to 0.3
Cramer et al. (2007b)*	23.4	N-A	8/10	480	KE	T (–60/–180°/s)	–0.03 (0.17)	–0.37 to 0.31	–0.4 (2.5)	–5.2 to 4.4
Cramer et al. (2007b)*	21.5	N-A	7/14	480	KE	T (60/240°/s)	–0.12 (0.20)	–0.51 to 0.27	–3.5 (2.6)	–8.5 to 1.6
Egan et al. (2006)*	20	A	0/11	480	KE	T (60/300°/s)	0.06 (0.24)	–0.42 to 0.54	1.0 (2.7)	–4.4 to 6.3
Evetovich et al. (2010)	19.9	A	0/15	480	KE	T (60°/s)	–0.24 (0.32)	–0.86 to 0.38	–7.1 (2.9)	–12.8 to –1.4
Evetovich et al. (2010)	21	A	0/14	480	KE	T (60°/s)	–0.21 (0.26)	–0.73 to 0.31	–5.3 (3.6)	–12.4 to 1.9
Evetovich et al. (2003)*	22.7	N-A	10/8	360	EF	T (30/270°/s)	–0.14 (0.22)	–0.58 to 0.30	–6.2 (4.0)	–14.1 to 1.7
Fletcher and Monte-Colombo (2010a)	20.8	A	21/0	30 (30–60)	PF, KE, KF, HE,HF	T (30°/s)	–0.14 (0.17)	–0.48 to 0.20	–3.6 (1.8)	–7.2 to 0.0
Fowles et al. (2000)	21	N-A	8/4	1755	PF	T	–1.27 (1.40)	–4.01 to 1.47	–27.7 (3.0)	–33.5 to –21.9
Gurjao et al. (2009)	64.6	N-A	0/23	90	KE, KF, HE	T	–1.31 (1.99)	–5.21 to 2.59	–7.6 (0.6)	–8.7 to –6.6
Herda et al. (2010)	23	N-A	11/0	360	PF	T	–0.60 (0.64)	–1.85 to 0.65	–9.4 (2.1)	–13.5 to –5.2
Herda et al. (2009)	24	N-A	15/0	1200	PF	T	–0.52 (0.64)	–1.77 to 0.73	–10.2 (2.1)	–14.4 to –6.1
Herda et al. (2008)*	25	N-A	14/0	1215	KF	T	–0.25 (0.30)	–0.84 to 0.34	–6.5 (2.4)	–11.2 to –1.8
Kay and Blazevich (2008)*	25.5	N-A	4/3	30 (5–60)	PF	T (180°/s)	–0.31 (0.26)	–0.83 to 0.21	–7.0 (3.1)	–13.0 to –1.0
Kay and Blazevich (2009b)	20.2	N-A	8/7	180	PF	T (5°/s)	–	–	–5.0 (1.2)	–7.3 to –2.7
Knudson and Noffal (2005)*	N/A	N-A	33/24	10	WF	F	–0.31 (0.41)	–1.12 to 0.50	–8.5 (1.45)	–11.3 to –5.6
Kokkonen et al. (1998)*	22	N-A	15/15	90	PF, KE, KF, HF	1RM	–0.25 (0.44)	–1.1 to 0.60	–7.9 (2.4)	–12.5 to –3.3
Kubo et al. (2001)	25.3	N-A	7/0	600	PF	T	–0.17 (0.22)	–0.61 to 0.27	–1.9 (1.9)	–5.6 to 1.9

Table 1. (continued)

Study	Age (years)	Fitness level	Sample size M/F	Duration of stretch (s)	Stretched muscle groups	Performance measure	Effect size (SE)	95% CI	% change (SE)	95% CI
Maisetti et al. (2007)	25	N-A	0/11	75	PF	T	–0.54 (0.58)	–1.68 to 0.60	–8.5 (2.0)	–12.3 to –4.6
Marek et al. (2005)*	23	N-A	9/10	480	KE	T (60/300°/s)	–0.02 (0.10)	–0.22 to 0.18	–0.9 (4.3)	–9.3 to 7.4
McBride et al. (2007)*	21.4	N-A	8/0	270	KE	F	–0.50 (0.47)	–1.42 to 0.42	–11.9 (3.5)	–18.7 to –5.0
Molacek et al. (2010)*	19.9	A	15/0	95 (40–150)	UB	1RM	–0.05 (0.14)	–0.33 to 0.23	–0.6 (1.2)	–3.0 to 1.8
Nelson et al. (2005c)*	22	N-A	18/13	360	PF, KE, KF, HF	1RM	–0.14 (0.24)	–0.62 to 0.34	–4.4 (2.4)	–9.0 to 0.3
Nelson et al. (2001a)*	22	N-A	25/30	480	KE	T	–0.03 (0.10)	–0.23 to 0.17	–1.3 (1.9)	–5.0 to 2.4
Nelson et al. (2001b)*	24	N-A	10/5	90	KE	T	–0.39 (0.50)	–1.37 to 0.59	–9.2 (2.4)	–13.9 to –4.5
Ogura et al. (2007)*	20	A	10/0	30	KF	F	–0.43 (0.45)	–1.31 to 0.45	–5.4 (1.6)	–8.5 to –2.3
Papadopoulos et al. (2005)	20.7	N-A	32/0	180 (90–180)	KE, KF	T (30°/s)	–0.31 (0.42)	–1.14 to 0.52	–4.5 (0.9)	–6.2 to –2.8
Papadopoulos et al. (2006)	19.7	N-A	10/0	90	PF, KE, KF, HF	F	–0.03 (0.14)	–0.31 to 0.25	–0.8 (3.8)	–8.3 to 6.7
Power et al. (2004)	32	N-A	12/0	270	PF, KE, KF	F	–0.49 (0.55)	–1.56 to 0.58	–9.0 (2.5)	–13.9 to –4.0
Ryan et al. (2008b)*	22	N-A	7/6	120	PF	T	–0.30 (0.33)	–0.95 to 0.35	–4.7 (3.2)	–10.9 to 1.6
Sekir et al. (2010)*	20	A	0/10	80	KE, KF	T (60/180°/s)	–0.42 (0.32)	–1.04 to 0.20	–9.8 (2.2)	–14.2 to –5.4
Siatras et al. (2008)*	22.1	N-A	20/0	10	KE	T	0.06 (0.17)	–0.28 to 0.40	1.4 (1.9)	–2.4 to 5.2
Siatras et al. (2008)*	21	N-A	20/0	20	KE	T	–0.14 (0.17)	–0.48 to 0.20	–2.9 (2.2)	–7.1 to 1.4
Siatras et al. (2008)*	21.1	N-A	20/0	30	KE	T	–0.71 (0.59)	–1.87 to 0.45	–6.6 (1.2)	–8.9 to –4.3
Siatras et al. (2008)*	21.1	N-A	20/0	60	KE	T	–0.82 (0.67)	–2.13 to 0.49	–12.5 (1.8)	–16.0 to –8.9
Thigpen (1989)*	27.3	N-A	12/12	90	KF	T (60/150/240°/s)	–0.01 (0.10)	–0.21 to 0.19	–0.2 (1.42)	–3.0 to 2.6
Torres et al. (2008)	19.6	A	11/0	30	UB	F	0.21 (0.26)	–0.31 to 0.73	3.2 (2.2)	–1.0 to 7.5
Viale et al. (2007)	23.1	N-A	7/1	390	KE	T	–0.46 (0.45)	–1.34 to 0.42	–8.0 (2.6)	–13.2 to –2.9
Weir et al. (2005)	23.1	N-A	0/15	600	PF	T	–0.42 (0.53)	–1.46 to 0.62	–7.1 (1.9)	–10.8 to –3.3
Winchester et al. (2009)*	22.5	N-A	10/8	105 (30–180)	KF	1RM	–0.25 (0.26)	–0.77 to 0.27	–8.9 (2.6)	–13.9 to –3.8
Yamaguchi et al. (2006)*	23.8	N-A	12/0	720	KE, HF	T	–0.02 (0.20)	–0.41 to 0.37	–0.7 (1.4)	–3.4 to 2.1
Zakas et al. (2006b)*	18.5	A	14/0	172 (45–300)	KE	T (60/90/150/210/270°/s)	–0.31 (0.24)	–0.79 to 0.17	–4.3 (1.3)	–6.8 to –1.9
Zakas et al. (2006a)*	13	A	16/0	60	KE	T (30/60/120/180/300°/s)	–0.29 (0.30)	–0.88 to 0.30	–4.2 (1.1)	–6.5 to –2.0
Zakas et al. (2006d)*	25	A	15/0	270 (30–480)	KE	T (60/90/150/210/270°/s)	–0.25 (0.26)	–0.77 to 0.27	–3.5 (1.2)	–5.9 to –1.2
Overall mean (all)	**22.9**	**–**	**10/6**	**314**	**–**	**–**	**–0.10 (0.03)**	**–0.15 to –0.04**	**–5.4 (0.6)**	**–6.6 to –4.2**

*Study that reported more than one primary outcome.

A, athletes; N-A, non-athletes; PF, ankle plantar flexors; KE, knee extensors; KF, knee flexors; HE, hip extensors; HF, hip flexors; UB, upper body; WF, wrist flexors; 1 RM, one repetition maximum; F, peak force; T, peak torque; CI, confidence interval; SE, standard error.

Table 2. Summary of the investigations included in the meta-analyses of acute effects of static stretching on muscle power

Study	Age (years)	Fitness level	Sample size M/F	Duration of stretch (s)	Stretched muscle groups	Performance measure	Effect size (SE)	95% CI	% change (SE)	95% CI
Muscle power										
Chaouachi et al. (2010)*	20.6	A	22/0	60	PF, KE, KF, HE, HF	MP	0.17 (0.27)	–0.35 to 0.70	1.6 (0.9)	–0.1 to 3.3
Cornwell et al. (2001)*	20.6	N-A	10/0	90	KE, HE	PP	–0.18 (0.22)	–0.61 to 0.26	–2.9 (2.2)	–7.1 to 1.4
Cramer et al. (2007b)*	23.4	N-A	15/0	480	KE	MP	–0.03 (0.17)	–0.36 to 0.30	–0.4 (2.5)	–5.2 to 4.4
Cramer et al. (2005)*	21.5	N-A	7/14	480	KE	MP	–0.12 (0.30)	–0.71 to 0.46	–2.7 (3.0)	–8.7 to 3.2
Egan et al. (2006)*	20.0	A	0/11	480	KE	MP	–0.04 (0.22)	–0.46 to 0.38	0.2 (5.0)	–9.6 to 10.1
Manoel et al. (2008)*	24.0	N-A	0/12	90	KE	MP	–0.13 (0.19)	–0.49 to 0.24	–2.9 (2.8)	–8.5 to 2.7
Marek et al. (2005)*	22.0	N-A	9/10	480	KE	MP	–0.04 (0.11)	–0.26 to 0.19	–1.5 (4.0)	–9.3 to 6.23
O'Connor et al. (2006)	21.4	N-A	16/11	30 (20–40)	PF,KE,KF,HE,HF	MP	0.13 (0.23)	–0.32 to 0.57	6.1 (4.5)	–2.7 to 14.8
Samuel et al. (2008)	22.0	N-A	12/12	90	KE,KF	MP	–1.89 (2.93)	–7.63 to 3.85	–3.4 (0.2)	–3.7 to –3.1
Torres et al. (2008)	19.6	A	11/0	30	UB	PP	0.14 (0.20)	–0.25 to 0.53	2.2 (2.2)	–2.1 to 6.5
Yamaguchi and Ishii (2005)	22.8	N-A	11/0	30	PF, KE, KF, HE, HF	MP	–0.27 (0.31)	–0.89 to 0.35	–5.1 (2.4)	–9.8 to –0.5
Yamaguchi et al. (2006)*	23.8	N-A	12/0	720	KE, HF	PP	–0.44 (0.40)	–1.23 to 0.35	–8.2 (1.7)	–11.6 to –4.8
Overall mean	**21.8**	**–**	**10/6**	**255**	**–**	**–**	**–0.04 (0.06)**	**–0.16 to 0.08**	**–1.9 (1.1)**	**–4.0 to 0.2**

*Study that reported more than one primary outcome.

A, athletes; N-A, non-athletes; PF, ankle plantar flexors; KE, knee extensors; KF, knee flexors; HE, hip extensors; HF, hip flexors; UB, upper body.; MP, mean power; PP, peak power; CI, confidence interval; SE, standard error.

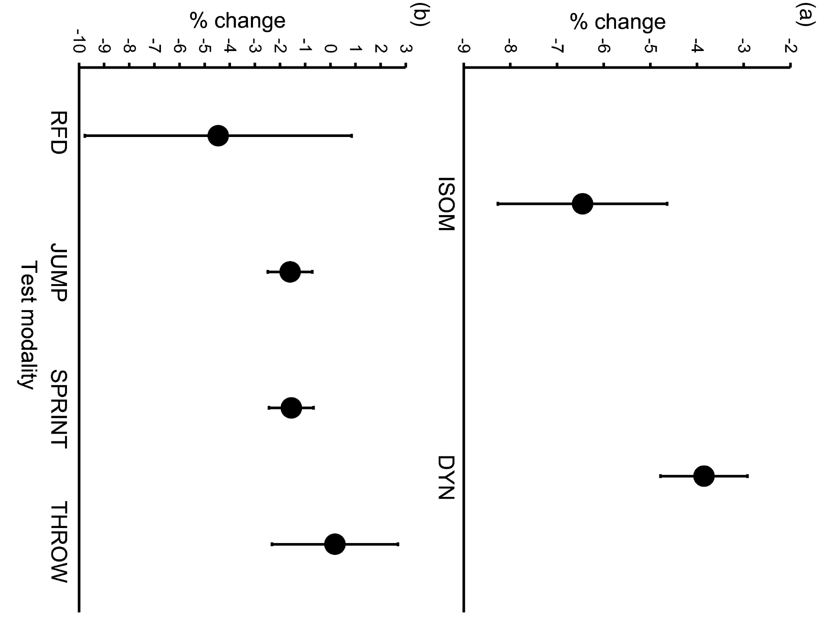

Fig. 1. Meta-analyzed acute effects of static stretching on maximal muscle strength tests (a) and explosive muscular performance tests (b). ISOM, isometric muscle strength; DYN, dynamic muscle strength; RFD, rate of force or torque development; JUMP, jumping performance; SPRINT, sprinting performance; THROW, throwing performance.

Explosive muscular performance

For all explosive muscular performance tests, pooled estimate of the acute effect of SS was $d = -0.03$ (95% CI: –0.07 to 0.01). When expressed in percentages, the respective pooled estimate was –2.0% (95% CI: –2.8% to –1.3%), indicating a very likely negative acute effect of SS on explosive muscular performance. We also observed very low heterogeneity of acute effects of SS on muscle power ($I^2 = 1.7\%$). Kendall's τ statistic ($r = -0.03$; $P = 0.71$) suggests no presence of publication bias in this performance category. However, a close inspection of the funnel plot recognized one study that had unrealistically large negative acute effect of SS on explosive performance ($d = -1.1$; percent change = –38.4%; McBride et al., 2007). Although its exclusion did not change the overall acute effect of SS on explosive muscular performance, it did affect two subgroup meta-analyses (i.e., groups based on the type of test and stretch duration, respectively). We therefore removed that study from those analyses. Subgroup analyses showed similar acute effect of SS on explosive muscular performance in both athletes and non-athletes ($P = 0.81$). With respect to the type of test applied, significant differences ($P < 0.05$)

Table 3. Summary of the investigations included in the meta-analyses of acute effects of static stretching on explosive muscular performance

Study	Age (years)	Fitness level	Sample size M/F	Duration of stretch (s)	Stretched muscle groups	Performance test	Effect size (SE)	95% CI	% change (SE)	95% CI
Jump										
Allison et al. (2008)	25.0	A	10/0	240 (240–360)	PF, KE, KF, HF	CMJ	–0.50 (0.52)	–1.52 to 0.52	–5.4 (1.5)	–8.3 to –2.5
Behm and Kibele (2007)	27.6	N-A	7/3	120	PF, KE, KF	SJ, DJ, CMJ	–0.29 (0.24)	–0.76 to 0.19	–4.7 (1.7)	–8.0 to –1.3
Behm et al. (2006)	25.0	N-A	9/9	90	PF, KE, KF	DJ	–0.08 (0.15)	–0.36 to 0.21	–2.0 (2.7)	–7.3 to 3.3
Behm et al. (2006)	21.9	N-A	12/0	90	PF, KE, KF	DJ, CMJ	–0.02 (0.31)	–0.63 to 0.60	1.1 (3.34)	–5.5 to 7.8
Bradley et al. (2007)	24.3	N-A	18/0	120 (120–240)	PF,KE,KF	CMJ, SJ	–0.12 (0.19)	–0.49 to 0.26	–4.0 (3.3)	–10.6 to 2.6
Brandenburg et al. (2007)	22.3	N-A	8/8	90	PF, KE, KF	CMJ	–0.15 (0.22)	–0.57 to 0.28	–3.0 (2.2)	–7.3 to 1.4
Burkett et al. (2005)	20.0	A	29/0	60	PF, KE, KF, HE, HF	CMJ	0.08 (0.15)	–0.22 to 0.38	0.7 (0.8)	–0.8 to 2.3
Chaouachi et al. (2010)*	20.6	A	22/0	60	PF, KE, KF, HE, HF	HJ, CMJ	0.01 (0.11)	–0.20 to 0.22	0.2 (0.7)	–1.3 to 1.6
Church et al. (2001)	20.3	A	0/40	n-a	KE, KF, HE, HF	CMJ	–1.31 (7.73)	–16.46 to 13.83	–1.2 (1.1)	–3.5 to 1.0
Cornwell et al. (2001)*	20.6	N-A	10/0	90	KE, HE	CMJ, SJ	–0.50 (0.51)	–1.49 to 0.49	–4.4 (1.2)	–6.8 to –2.0
Cornwell et al. (2002)*	22.5	N-A	10/0	180	PF	CMJ, SJ	–0.15 (0.24)	–0.61 to 0.31	–4.1 (4.0)	–11.9 to 3.8
Cronin et al. (2008)	22.7	A	10/0	90	KF	CMJ	0.00 (0.14)	–0.28 to 0.28	0.0 (3.9)	–7.7 to 7.7
Curry et al. (2009)	26.0	N-A	0/23	36	PF, KE, KF, HE, HF	CMJ	–0.18 (0.30)	–0.76 to 0.40	–2.9 (1.4)	–5.6 to –0.1
Dalrymple et al. (2010)	19.5	A	0/12	45	PF, KE, KF, HE	CMJ	–0.20 (0.25)	–0.70 to 0.30	–3.2 (2.1)	–7.3 to 0.8
Di Cagno et al. (2010)	14.1	A	0/38	90 (90–180)	PF,KE,KF	SJ	0.00 (0.05)	–0.10 to 0.10	0.0 (0.3)	–0.5 to 0.5
Fletcher and Monte-Colombo (2010a)	20.8	A	21/0	30 (30–60)	PF, KE, KF, HE, HF	CMJ	–0.37 (0.52)	–1.39 to 0.66	–4.3 (1.1)	–6.4 to –2.2
Fletcher and Monte-Colombo (2010b)	20.5	A	27/0	30 (30–60)	PF, KE, KF, HE, HF	CMJ	–0.38 (0.64)	–1.64 to 0.87	–4.1 (0.9)	–5.8 to –2.3
Gonzalez-Rave et al. (2009)*	21.8	N-A	8/0	45	PF, KE, KF	CMJ, SJ	0.58 (0.41)	–0.22 to 1.39	8.3 (1.7)	4.9 to 11.6
Handrakis et al. (2010)*	49.9	N-A	6/4	90	PF, KE, KF, HE	HJ	0.00 (0.14)	–0.27 to 0.26	–0.1 (1.9)	–3.8 to 3.6
Holt and Lambourne (2008)	20.7	A	64/0	15	KE,KF,HE,HF	CMJ	0.13 (0.20)	–0.26 to 0.53	1.6 (1.4)	–1.1 to 4.3
Hough et al. (2009)	21.0	A	11/0	30	PF, KE, KF, HE, HF	SJ	–0.25 (0.29)	–0.82 to 0.32	–4.3 (2.2)	–8.7 to 0.1
Kinser et al. (2008)*	11.3	A	0/8	40	HF, HE, KF	CMJ, SJ	–0.34 (0.34)	–1.00 to 0.32	–6.0 (2.4)	–10.6 to –1.3
Knudson et al. (2001)	23.7	A	10/10	135	PF, KE, KF	CMJ	–0.30 (0.44)	–1.16 to 0.56	–4.2 (1.4)	–7.0 to –1.4
Koch et al. (2003)	20.0	A	16/16	160	KE, KF	HJ	0.00 (0.08)	–0.15 to 0.15	0.0 (2.1)	–4.1 to 4.1
La Torre et al. (2010)*	23.0	A	17/0	120	PF, KE	SJ	–0.22 (0.27)	–0.75 to 0.31	–7.4 (2.3)	–12.0 to –2.9
Little and Williams (2006)	n/a	A	18/0	30	PF, KE, KF, HE, HF	CMJ	–0.21 (0.30)	–0.80 to 0.38	–2.5 (1.2)	–4.9 to –0.1
Mcmillian et al. (2006)	20.2	N-A	16/14	30	UB, PF, KE, KF, HE, HF	HJ	0.26 (0.45)	–0.63 to 1.14	3.2 (1.0)	1.2 to 5.1
McNeal and Sands (2003)	13.3	A	0/13	90 (60–90)	PF,KF	DJ	–0.56 (0.69)	–1.92 to 0.80	–9.6 (2.7)	4.2 to 15.0
Murphy et al. (2010)	26.0	N-A	11/0	36	PF,KE,HE	CMJ	0.37 (0.41)	–0.44 to 1.18	4.2 (1.5)	1.2 to 7.1
Pearce et al. (2009)	22.5	N-A	11/2	60	PF, KE, KF, HE, HF	CMJ	–0.37 (0.43)	–1.22 to 0.49	–7.8 (2.5)	–12.7 to –2.9
Robbins and Scheuermann (2008)*	20.3	A	10/10	60 (30–90)	PF, KE, KF	SJ	–0.12 (0.16)	–0.44 to 0.20	–2.1 (1.4)	–4.7 to 0.6
Samuel et al. (2008)	22.0	N-A	12/12	90	KE,KF	CMJ	–0.07 (0.17)	–0.40 to 0.26	–	–
Unick et al. (2005)*	19.2	A	0/16	90 (45–90)	PF, KE, KF	CMJ, DJ	0.13 (0.19)	–0.25 to 0.51	1.9 (1.6)	–1.2 to 4.9
Vetter (2007)	22.3	N-A	14/12	30	PF, KE, KF, HE	CMJ	–0.10 (0.19)	–0.47 to 0.27	–0.8 (0.7)	–2.2 to 0.5
Wallman et al. (2005)	26.0	N-A	8/6	90	PF	CMJ	–0.23 (0.29)	–0.80 to 0.35	–5.6 (2.9)	–11.4 to 0.1
Wallman et al. (2008)	26.0	N-A	7/6	90	PF	CMJ	0.09 (0.16)	–0.23 to 0.41	2.9 (3.8)	–4.6 to 10.4
Young and Behm (2003)*	26.0	N-A	13/4	120	PF, KE	SJ, DJ	–0.21 (0.29)	–0.77 to 0.35	–3.2 (1.8)	–6.7 to 0.3
Young and Elliott (2001)	22.0	A	14/0	45	PF, KE, HE	SJ	–0.19 (0.26)	–0.70 to 0.31	–1.9 (1.2)	–4.2 to 0.4
Young et al. (2006)*	22.8	N-A	12/8	60	PF	DJ	–0.17 (0.21)	–0.58 to 0.24	–3.5 (1.5)	–6.5 to –0.5
Overall jump	**22.5**	**–**	**12/7**	**79**	**–**	**–**	**–0.03 (0.03)**	**–0.08 to 0.02**	**–1.6 (1.5)**	**–2.5 to –0.7**

Table 3. (continued)

Study	Age (years)	Fitness level	Sample size M/F	Duration of stretch (s)	Stretched muscle groups	Performance test	Effect size (SE)	95% CI	% change (SE)	95% CI
RFD										
Alpkaya and Koceja (2007)	25.1	N-A	14/1	90	PF	RFD	0.12 (0.19)	–0.25 to 0.49	3.9 (3.9)	–3.8 to 11.6
Bazett-Jones et al. (2005)	20.6	A	10/0	90	KE, KF, HF	RFD	0.04 (0.15)	–0.25 to 0.32	0.9 (3.6)	–6.2 to 8.0
Gurjao et al. (2009)	64.6	N-A	0/23	90 (90–180)	KE,KF,HE	RFD	–1.28 (1.94)	–5.08 to 2.52	–14.1 (1.1)	–16.2 to –11.9
Maisetti et al. (2007)*	25.0	N-A	0/11	75	PF	RFD	0.09 (0.13)	–0.16 to 0.34	4.1 (5.0)	–5.8 to 14.0
McBride et al. (2007)	21.4	N-A	8/0	99	KE	RFD	–1.07 (0.97)	–2.97 to 0.83	–38.4 (5.5)	–49.2 to –27.5
Papadopoulos et al. (2006)	19.7	N-A	10/0	180 (90–180)	PF, KE, KF, HF	RFD	–0.13 (0.19)	–0.51 to 0.25	–3.6 (3.7)	–10.8 to 3.6
Yamaguchi et al. (2006)*	23.8	N-A	12/0	720	KE, HF	RFD	–0.41 (0.37)	–1.13 to 0.32	–16.4 (3.2)	–22.7 to –10.1
Young and Behm (2003)	26.0	N-A	13/4	120	PF, KE	RFD	–0.08 (0.15)	–0.37 to 0.21	–2.7 (3.8)	–10.2 to 4.8
Young and Elliott (2001)	22.0	A	14/0	45	PF, KE, HE	RFD	–0.23 (0.30)	–0.83 to 0.36	–6.1 (3.0)	–11.9 to –0.3
Young et al. (2006)*	22.8	N-A	12/8	60	PF	RFD	–0.09 (0.17)	–0.43 to 0.25	–2.3 (2.2)	–6.6 to 2.0
Overall RFD	**27.1**	**–**	**9/5**	**157**	**–**	**–**	**–0.02 (0.06)**	**–0.14 to 0.10**	**–4.5 (2.7)**	**–9.8 to 0.9**
Sprint§										
Chaouachi et al. (2010)	20.6	A	22/0	60	PF, KE, KF, HE, HF	Sprint 5, 10, 30 m	–0.42 (0.53)	–1.45 to 0.62	–2.4 (0.5)	–3.3 to –1.4
Chaouachi et al. (2008)	14.0	N-A	24/24	40	KE,KF	Sprint 10 m	–0.12 (0.26)	–0.63 to 0.39	–0.8 (0.4)	–1.7 to 0.1
Favero et al. (2009)*	22.0	A	10/0	90	PF, KE, KF, HE, HF	Sprint 10,40 m	–0.10 (0.19)	–0.47 to 0.27	–0.6 (0.8)	–2.1 to 0.9
Fletcher and Jones (2004)	23.0	A	28/0	20	PF, KE, KF, HE, HF	Sprint 20 m	–0.24 (0.40)	–1.00 to 0.52	–1.2 (0.45)	–2.1 to –0.3
Fletcher and Jones (2004)	23.0	A	24/0	20	PF, KE, KF, HE, HF	Sprint 20 m	–0.26 (0.41)	–1.06 to 0.54	–1.5 (0.55)	–2.6 to –0.4
Fletcher and Monte-Colombo (2010a)	20.8	A	21/0	30	PF,KE, KF,HE,HFADD,ABD	Sprint 20 m	0.00 (0.09)	–0.17 to 0.17	0.0 (0.8)	–1.5 to 1.5
Gelen (2010)	23.3	A	26/0	50	PF,KE,KF,HE,HF,ADD	Sprint 30 m	–1.18 (1.90)	–4.90 to 2.54	–8.5 (0.6)	–9.7 to 7.3
Kistler et al. (2010)	20.3	A	18/0	180	PF,KE,KF	Sprint 40 m	–0.61 (0.68)	–1.94 to 0.72	–1.4 (0.2)	–1.8 to –1.0
Little and Williams (2006)*	n/a	A	18/0	30	PF, KE, KF, HE, HF	Sprint 10, 20 m	0.00 (0.10)	–0.20 to 0.20	0.0 (0.5)	–0.9 to 0.9
Nelson et al. (2005a)*	20.0	A	11/5	120	PF, KF, HE	Sprint 20 m	0.00 (0.09)	–0.17 to 0.17	0.0 (0.1)	–0.2 to 0.2
Sayers et al. (2008)	19.4	A	0/20	90	PF,KE,KF	Sprint 30 m	–0.37 (0.53)	–1.42 to 0.67	–2.1 (0.6)	–3.2 to 1.0
Siatras et al. (2003)*	9.8	A	11/0	30	PF, DF, KE, KF	Sprint 5–15 m	0.18 (0.18)	–0.18 to 0.54	3.2 (1.9)	–0.5 to 6.9
Vetter (2007)	22.3	N-A	14/12	30	PF, KE, KF, HE	Sprint 30 m	–0.14 (0.25)	–0.63 to 0.34	–2.0 (1.3)	–4.5 to 0.5
Winchester et al. (2008)*	20.3	A	11/11	90	PF, KE, KF, HE	Sprint 20–40 m	–0.08 (0.16)	–0.40 to 0.24	–0.6 (1.3)	–3.2 to 2.0
Overall sprint§	**19.9**	**–**	**16/6**	**63**	**–**	**–**	**–0.04 (0.04)**	**–0.13 to 0.05**	**–1.6 (0.5)**	**–2.6 to –0.5**
Throwing										
Haag et al. (2010)	20.3	A	12/0	30	UB	Throwing	0.47 (0.53)	–0.57 to 1.52	1.7 (0.5)	0.8 to 2.6
Mcmillian et al. (2006)	20.2	N-A	16/14	30	UB, PF, KE, KF, HE, HF	Throwing	–0.07 (0.14)	–0.35 to 0.21	–2.1 (2.5)	–6.9 to 2.7
Torres et al. (2008)*	19.6	A	11/0	30	UB	Throwing	–0.13 (0.26)	–0.63 to 0.37	–1.2 (1.7)	–4.5 to 2.2
Overall throw	**20.0**	**–**	**13/5**	**30**	**–**	**–**	**–0.05 (0.12)**	**–0.29 to 0.19**	**0.2 (1.3)**	**–2.3 to 2.7**
Overall mean (all tests)	**22.8**	**–**	**12/6**	**86**	**–**	**–**	**–0.03 (0.02)**	**–0.08 to 0.01**	**–2.0 (0.4)**	**–2.8 to –1.3**

*Study that reported more than one primary outcome.

§Sprint time, an inversely scaled variable, has been rescaled before meta-analysis.

A, athletes; N-A, non-athletes; ADD, hip adductors; ABD, hip abductors; PF, ankle plantar flexors; DF, ankle dorsiflexors; KE, knee extensors; KF, knee flexors; HE, hip extensors; HF, hip flexors; UB, upper body; CMJ, countermovement jump; DJ, depth jump; HJ, horizontal jump; SJ, squat jump; RFD, rate of force or torque development; CI, confidence interval; SE, standard error.

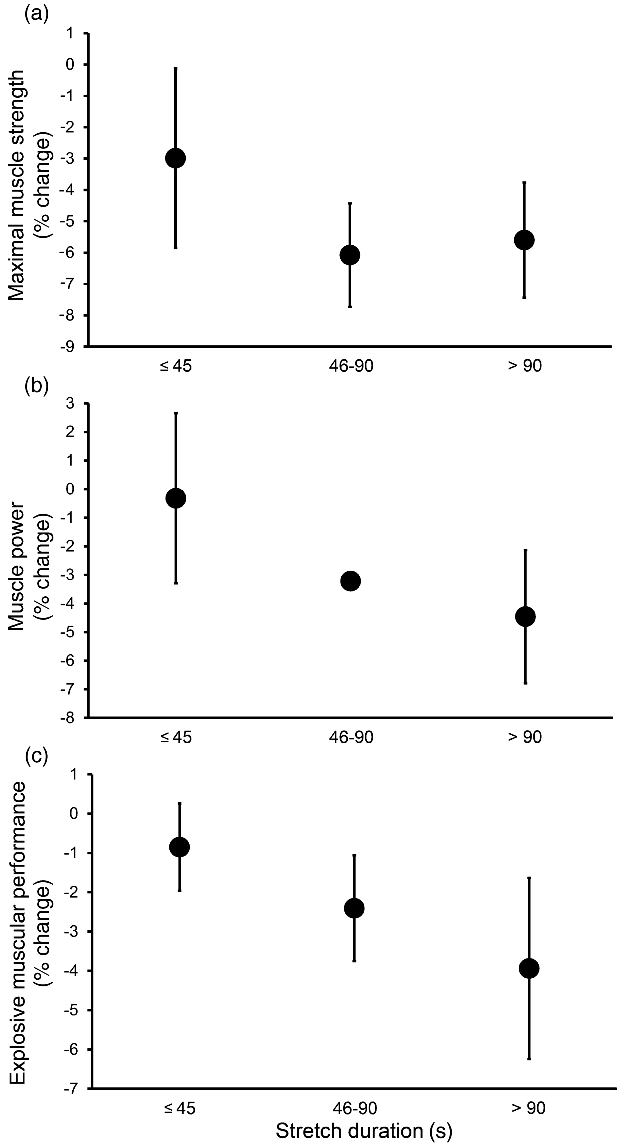

Fig. 2. Meta-analyzed acute effects of different duration of static stretching on maximal muscle strength (a), muscle power (b), and explosive muscular performance (c).

in pooled negative acute effects of SS were observed among four different explosive performance categories (Fig. 1(b)). Specifically, pooled estimates for the acute effect of SS on RFD, jump, sprint, and throw performance were –4.5% (95% CI: –9.8% to 0.8%; possibly negative effect), –1.6% (95% CI: –2.5% to –0.7%; a likely harmful effect), –1.6% (95% CI: –2.6% to –0.5%; a likely harmful effect), and 0.2% (95% CI: –2.3% to 2.7%; an unclear effect), respectively. Note that the observed magnitudes of stretch-induced changes, particularly explosive muscular performance tests, are in agreement with the corresponding average stretch duration per muscle group (i.e., 157, 79, 63, and 30 s for RFD, jump, sprint, and throw performance; see Table 3). With respect to the stretch duration, we observed a significant ($P = 0.0001$) reduction in the negative acute effect of SS on explosive muscular performance with shorter stretch duration (Fig. 2(c)). In particular, pooled estimates for the acute effect of SS lasting ≤45, 46–90, and >90 s per muscle group on explosive performance were –0.8% (95% CI: –2.0% to 0.5%; possibly negative effect), –2.5% (95% CI: –3.8% to –1.1%; almost certainly negative effect), and –4.5% (95% CI: –7.3% to –1.7%; almost certainly negative effect), respectively.

Meta-regressions

Significant negative relationships (all $P < 0.001$) were found between the total stretch duration per muscle group and individual study estimates in all three categories of muscular performance tests (Fig. 3). As mentioned already, subject's age and gender were not significantly related to study estimates in selected primary outcomes (all $P > 0.05$).

Discussion

This meta-analytical review provides clear evidence from 104 studies that (a) pre-exercise SS induces significant and practically relevant negative acute effects on maximal muscle strength and explosive muscular performance, regardless of subject's age, gender, or training status, while the corresponding acute effects of SS on muscle power are still unclear; (b) the acute effects of SS on maximal muscular performance are task-specific, with type of muscle contraction (isometric vs dynamic) being an important factor; and (c) negative acute effects of acute SS on maximal muscular performance tend to diminish with reduction of stretch duration. Prior to discussing these main findings, some methodological issues deserve to be discussed.

While a meta-analysis will yield a mathematically accurate synthesis of the studies included in the analysis, if these studies are a biased sample of all relevant studies, the mean effect computed by the meta-analysis will reflect this bias (Borenstein et al., 2009). In the present study, we found no evidence of publication bias in selected primary outcomes. Furthermore, there was a low heterogeneity of effect within each meta-analysis, suggesting that all trails generally examined the same effects. These issues generally support the robustness of our results; however, we have to acknowledge that we selected only studies published in peer-reviewed journals; thus, there is likelihood that some smaller studies without significant effects remained unpublished. Also, our meta-analytical review may have been biased by inclusion only of studies reported in English. In that regard, some caution is still warranted regarding the precise estimates of the acute effects of SS on selected muscular performance tests.

The major finding of this meta-analytical review is related to a precise quantitative estimate of the acute

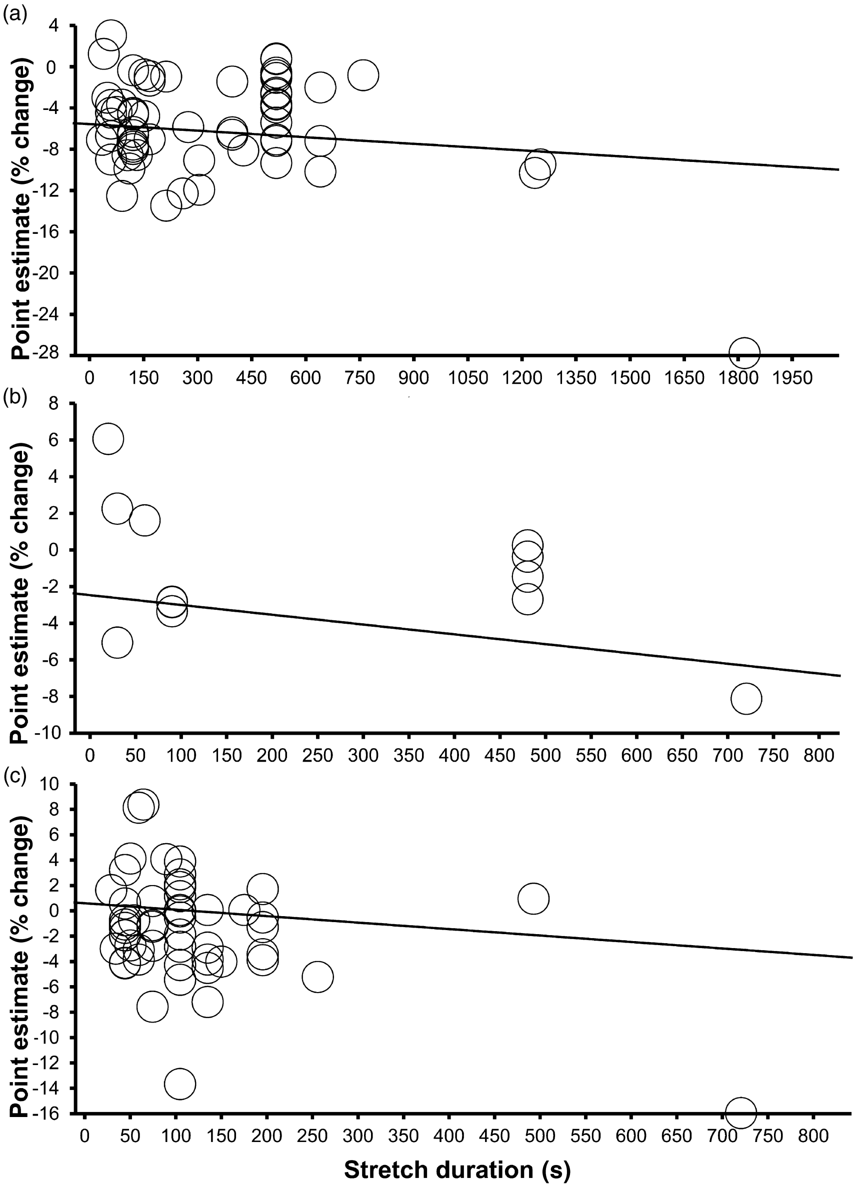

Fig. 3. Relationship between static stretch-induced change in performance (%) and the total duration of stretching in (a) maximal muscle strength tests, (b) muscle power tests, and (c) explosive muscular performance tests.

effects of SS on maximal muscular performance. Overall, our results indicate that an acute bout of SS decreases maximal muscle strength, muscle power, and explosive muscular performance by –5.4% (95% CI: –6.6% to –4.2%), –1.9% (95% CI: –4.0% to 0.2%), and –2.0% (95% CI: –2.8% to –1.3%), respectively. Based on the corresponding 95% CI, and selected thresholds for minimal practically relevant change in athlete's muscular performance (i.e., 5%, 1%, and 1%, respectively), we can conclude that these acute effects of SS were statistically significant and practically relevant for maximal muscle strength (a likely negative acute effect) and explosive muscular performance (a very likely negative acute effect), but not for muscle power (an unclear effect). More studies are needed to clarify the acute effects of SS on muscle power. More importantly, this study shows that the observed stretch-induced reductions in maximum muscular performance are generally independent of subject's age, gender, and training status, suggesting that they could be generalized to young and adult athletic, but also non-athletic population of both sexes. Obviously, factors other than age, sex, and training status (e.g., stretch duration and intensity, task specificity, etc.; see further paragraphs) are responsible for relatively high variability in research results on this topic (see the first paragraph). Without considering these factors, the above-discussed results of meta-analyses strongly suggest that the usage of SS as the sole activity during warm-up routine should generally be avoided. Given that even a small reduction in maximum muscular performance could be detrimental for competitive performance of high-level athletes in certain sports, this conclusion particularly goes for the athletic population. Previous narrative and/or systematic reviews on this topic also came to the same conclusion (Shrier, 2004; Magnusson & Renstrom, 2006; Rubini et al., 2007; McHugh & Cosgrave, 2010; Behm & Chaouachi, 2011; Kay & Blazevich, 2011), but without robust quantitative evidence, obtained using an appropriate statistical approach.

An important factor to consider when studying the acute effects of SS on maximal muscular performance is the type of performance test applied. In that regard, our results provide some new interesting findings related to the type of contraction. First, we have demonstrated that isometric maximal strength is significantly more negatively affected by an acute bout of SS compared with dynamic (concentric and eccentric) maximal strength. More interestingly, although not presented in the Results section, no evidence of contraction specificity in the acute effects of SS was found between the concentric vs eccentric maximal strength tests. As there were no significant differences in average stretch duration per muscle group between isometric and dynamic maximal strength tests, other factors are likely responsible for the observed contraction-specific acute effects of SS on maximal strength. We believe that the main candidate could be stretch-induced transient reduction in stiffness of the muscle-tendon complex (Weir et al., 2005; Ryan et al. 2008a). Specifically, a more compliant muscle-tendon complex would allow a less efficient transmission of force to the skeleton (Markovic & Mikulic, 2010), and this effect is likely to be more evident during isometric compared with dynamic maximal contractions. Consistent with this notion is the fact that significantly higher negative acute effects of SS were observed in RFD (isometric contraction) than in jump, sprint, or throw performance (dynamic, high-velocity contractions). Indeed, reduced RFD and prolonged electromechanical delay have been frequently associated with a reduction of musculotendinous stiffness (Costa et al., 2010; Herda et al., 2010). However, the above-mentioned difference could also be a result of noticeably higher mean stretch duration per muscle group in RFD tests compared with the remaining explosive muscular performance tests. Thus, more studies are needed to clarify this issue. In their recent review article, Behm and Chaouachi (2011) argued that the negative acute effects of SS could be lower in slow vs fast stretch-shortening cycle tasks. We found no evidence to support this viewpoint (see Table 3), although detailed quantitative analysis in this respect has not been performed. Finally, pooled estimate of the acute effects of SS on throwing performance, although seriously limited by the total number of meta-analyzed studies, suggest that these effects could be less harmful when compared with the corresponding acute effects on jumping and sprinting performance. Although more studies are definitely needed in this area, we may speculate that the high-velocity movements that require large operating ranges of motion (such as throwing) are much less adversely affected by an acute bout of SS. Theoretically speaking, for such movements, possible negative acute effects of SS on force-generating capacity of agonist muscle(s) could be counteracted by stretch-induced increase in active range of motion, thereby allowing muscles to perform similar amount of work during propulsion in both cases (i.e., pre- and post-stretching). Alternatively, one could simply argue that throwing represents a complex ballistic movement that requires sequential action of numerous lower-body, trunk and upper-body muscles, and that the acute SS of a particular upper-body muscle group has much less impact on performance. In that regard, it is interesting to note that the most prominent negative acute effects of SS on throwing performance among selected studies is seen in a study that applied SS of both upper- and lower-body muscles (see Table 3). These conjectures require further experimental verification.

Another important factor to consider when studying the acute effects of SS on maximal muscular performance is the total stretch duration per muscle group. In two most recent review papers, the authors argued that shorter-duration (<45 s per muscle group) pre-exercise SS might not be detrimental to performance (Behm & Chaouachi, 2011; Kay & Blazevich, 2011). However, without the use of an appropriate statistical tool for pooling the data from available SS studies, such conclusions lack firm scientific support. Results of our meta-analytical review indicate the existence of a dose–response relationship between stretch-induced performance decrements and average stretch duration per muscle group (see Figs 2 and 3), in line with the conclusions of several research studies (Ogura et al., 2007; Kay & Blazevich, 2008; Ryan et al. 2008b) and reviews (Behm & Chaouachi, 2011; Kay & Blazevich, 2011). In particular, stretch-induced negative acute effects on performance diminished with the reduction of stretch duration in all three groups of muscular performance tests; however, they still remained negative for two muscular performance categories. Thus, even short-duration pre-exercise SS (i.e., <45 s per muscle group) could possibly be harmful to muscular performance. So, we now come to an important question for clinicians and practitioners: *Should we completely exclude SS from warm-up routines that precede exercise or athletic events*? An answer to this question requires more than just acknowledging the results of the performed meta-analyses. Namely, we have to acknowledge that SS also has certain positive acute effects during warm-up – increased range of motion (McHugh & Cosgrave, 2010; Behm & Chaouachi, 2011) and reduced incidence of muscle strains (McHugh & Cosgrave, 2010). Indeed, based on a comprehensive literature review, McHugh and Cosgrave (McHugh & Cosgrave 2010) have recently concluded that pre-exercise SS is beneficial for reducing muscle strains. Thus, while the usage of SS (regardless of its duration) as the sole activity during warm-up should generally be avoided, its incorporation into a comprehensive warm-up could be a possible practical solution that would minimize the negative acute effects of SS on performance, while still keeping its potentially positive effects. Related to that, Chaouachi et al. (2008) have recently showed that the addition of short-duration (i.e., 20 s) SS of quadriceps and hamstring muscles into a warm-up routine for sprint training increased the range of motion and diminished the detrimental acute effects of SS on sprint performance compared with a sprint-only training program. Clearly, there is a need for additional well-designed studies that examine the acute effects of short-duration SS, incorporated into a comprehensive pre-exercise warm-up routine, on maximal muscular performance.

This study has certain limitations. First, the PEDro scores of the studies included in the meta-analyses suggest that most studies are prone to subject and/or researcher bias. Given that the ultimate quality of a meta-analysis depends of the quality of the primary studies on which it is based, our results need to be appreciated with an awareness of the limitations of the primary studies. However, we should take into account that blinding of participants and therapists is impossible in exercise interventions. If these two items were deleted from the PEDro scale, the quality ratings of all the included studies would have changed substantially. Nonetheless, we recommend that future stretching studies improve their quality by randomizing subjects into groups, blinding the assessors, as well as by ensuring that treatment allocation concealment and intention to treat analyses are performed. Second, our study did not address the effects of several relevant factors related to acute SS, including the SS intensity, the time from cessation of the warm-up to the performance test, the particular stretching exercises, and the time course of any stretch-induced effects (Young, 2007). These factors need to be addressed in future well-designed SS studies.

Conclusions and recommendations

Our results clearly show that SS before exercise has significant and practically relevant negative acute effects on maximal muscle strength and explosive muscular performance, while the corresponding acute effects on muscle power remain unclear. These findings are universal, regardless of the subject's age, gender, or training status. However, the magnitude of the static stretch-induced negative acute changes in performance was more pronounced in maximal isometric tests compared with maximal dynamic tests. Finally, the observed stretch-induced negative acute changes in selected muscular performance tests were related to the total duration of stretch, with the smallest negative acute effects being observed with stretch duration of $\leq$45 s, respectively. Based on the evidence from this study, we recommend that the usage of SS as the sole activity during warm-up routine should generally be avoided. Given the potential positive effect of pre-exercise SS on the reduction of incidence of muscle strains, further studies should examine the acute effects of SS of shorter duration (e.g., 15–30 s per muscle group), incorporated into a comprehensive pre-exercise warm-up routine, on maximal muscular performance.

Key words: warm-up, stretch, performance, acute effects.

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