Title

The effect of acute static stretch on maximal muscle performance: A systematic review

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ABSTRACT

Introduction: The benefits of pre-exercise muscle stretching have been recently questioned following reports of significant post-stretch reductions in force and power production. However, methodological issues and equivocal findings have prevented a clear consensus being reached. As no detailed systematic review exists, the literature describing responses to acute static muscle stretch was comprehensively examined.

Methods: Medline, ScienceDirect, SPORTDiscus and Zetoc were searched with recursive reference checking. Selection criteria included randomized or quasi-randomized controlled trials and intervention-based trials published in peer-reviewed scientific journals examining the effect of an acute static stretch intervention on maximal muscular performance.

Results: Searches revealed 4559 possible articles; 106 met the inclusion criteria. Study design was often poor as 30% of studies failed to provide appropriate reliability statistics. Clear evidence exists indicating that short-duration acute static stretch (<30 s) has no detrimental effect (pooled estimate = -1.1%), with overwhelming evidence that stretch durations of 30-45 s also imparted no significant effect (pooled estimate = -1.9%). A sigmoidal dose-response effect was evident between stretch duration and both the likelihood and magnitude of significant decrements, with a significant reduction likely to occur with stretches ≥60 s. This strong evidence for a dose-response effect was independent of performance task, contraction mode or muscle group. Studies have only examined changes in eccentric strength when the stretch durations were >60 s, with limited evidence for an effect on eccentric strength.

Conclusion: The detrimental effects of static stretch are mainly limited to longer durations (≥60 s) which may not be typically used during pre-exercise routines in clinical, healthy or athletic populations. Shorter durations of stretch (<60 s) can be performed in a pre-exercise routine without compromising maximal muscle performance.

Key Words: muscle strength, warm-up, force reduction, pre-performance stretch.

INTRODUCTION

Paragraph Number 1 It is well documented that both physical performance and injury risk can be altered by the performance of a complete pre-exercise routine (a warm-up) prior to intense physical work (3, 113). Static stretching increases range of motion and can also decrease musculotendinous stiffness, even during short-duration (5-30 s) stretches (7, 52). Furthermore, a recent review (70) has suggested that there is evidence that pre-performance stretching can reduce the risk of acute muscle strain injuries. However, given that multi-intervention pre-exercise routines commonly include cardiovascular work, progressively intense muscular contractions and muscle stretching, the specific element or combination of elements responsible for improving performance and reducing injury risk is impossible to ascertain. This issue has been raised in several reviews of the literature, which report equivocal findings regarding the benefits of muscle stretching as a preventative tool for injury risk (70, 99, 112). Furthermore, numerous publications have reported that acute passive static muscle stretch can induce significant reductions in low-speed (strength), moderate-speed (power) and higher-speed (speed) force production (10, 15, 21, 25, 28, 40, 52, 58, 59, 65, 69, 77, 78, 82, 96, 105, 107, 119). Accordingly, the inclusion of static stretching in a pre-exercise routine prior to the performance of maximal strength-, power- and/or speed-dependent activities is thought to negatively affect our ability to maximally perform simple and complex movements (movement performance).

Paragraph Number 2 A growing body of research has highlighted a detrimental effect of muscle stretching on maximal muscular performance, with some authors specifically examining stretch-induced force deficits in an attempt to identify the possible mechanical, physiological and neurological mechanisms underpinning these changes in force (40, 53, 54). This has resulted in the publication of a position statement by the European College of Sport Sciences (63), which concluded that there was firm evidence that an acute bout of stretching could diminish performance in tests requiring maximal muscle efforts. This finding is in agreement with an earlier systematic review (94), examining acute and chronic responses of various stretch modalities on muscular performance. However, a subsequent review by Rubini et al. (89) revealed equivocal effects of static, ballistic and proprioceptive neuromuscular facilitation (PNF) stretching on maximal force production. The authors concluded that while the majority of studies documented a deleterious effect on strength, the broad remit of their review (focussing on both acute and chronic effects, different stretch modalities and various durations) resulted in equivocal findings. Simultaneously, Young (120) specifically addressed the use of acute static stretching in pre-exercise routines and concluded that there were equivocal results regarding the effects of acute stretch, possibly resulting from major issues in research design (including a lack of control or reliability analysis) and the long, practically-irrelevant durations of the imposed stretches. A more recent review (70) examining the effects of various stretch modes on injury prevention and performance suggested that while stretching may reduce the acute incidence of muscle strain injuries, there was an abundance of literature demonstrating a negative effect of stretch on performance. Although collectively these four papers report equivocal effects of stretch on maximal force and power production, there is a predominant theme that acute muscle stretch can significantly impair muscle performance and that it should be used with caution in a pre-exercise routine. A consequence of the detrimental reports in the literature was a recent change in the American College of Sports Medicine’s guidelines (1) to suggest the removal of static stretching as part of a warm-up routine and to only include cardiovascular work when strength or power was important to performance.

Paragraph Number 3 Closer examination of these reviews revealed that relatively few studies were cited that specifically address the effects of acute static stretch (n = 17 (63); n = 32 (70); n = 36 (89); n = 21 (94); n = 21 (120)). To date, while other generic reviews exist examining the effects of various muscle stretching modes on performance and injury risk, no systematic review has focussed specifically on the acute effects of static stretching on maximal muscle efforts. Given that static muscle stretching is the most common form of pre-exercise stretching to be used in clinical, normal and athletic populations, there are a considerable number of methodological issues reported in the literature (120), and that numerous papers have been published since Rubini et al. (89) and Young et al. (120) published their findings in 2007 (n = 64), the aim of the present review was to provide a detailed systematic examination of the acute effects of passive static stretch on performance in strength-, power- and speed-dependent tasks. Furthermore, given the equivocal findings reported previously in the literature, the specific effects of static stretch duration, test contraction mode and the muscle group tested were examined.

METHODS

Search strategy

Paragraph Number 4 The latest PRISMA guidelines for conducting a systematic review (73) were followed including the four-step systematic approach of identification, screening, eligibility and inclusion. We used a federated search tool (Metalib) to search four databases concurrently (Medline [1966-2011], ScienceDirect [1823-2011], SPORTDiscus [1985-2011], and Zetoc [1993-2011]) for articles employing an acute static stretch-based intervention examining a maximal muscular performance outcome measure; we completed our last search on the 16th February 2011. Search terms within the article title were ‘static stretch*’, ‘acute stretch*’, ‘stretch* & effects’, ‘stretch* & force’, ‘stretch* & power’, and ‘stretch* & speed’. Additional searches were conducted on eligible articles using the first author’s surname and the search term ‘stretch*’ in the title, with recursive reference screening of eligible articles performed to identify other possibly relevant articles (*enables other ‘stretch’ word derivatives for example stretching, stretches etc. to be included).

Study selection and inclusion criteria

Paragraph Number 5 The review included original research articles examining the effects of an acute static stretch intervention on a maximal voluntary muscular performance outcome measure in strength-, power- and speed-dependent tasks. Randomized and quasi-randomized control trials (RCT) were included that met the PEDro inclusion criteria: 1) the comparison of at least two interventions, 2) that interventions were currently part of physiotherapy practice, 3) that interventions were applied to human subjects, 4) there was randomization of interventions, and 5) the article was a full paper published in a peer reviewed journal. Intervention-based studies examining pre- and post-stretch data that did not meet the first criterion (comparison of at least two interventions) were also included. One reviewer excluded obviously irrelevant articles by screening the titles and abstracts, with a 5% sample of the excluded articles verified by a second reviewer. Abstracts of the remaining articles were assessed by one reviewer, with articles selected for exclusion being verified by a second reviewer. Full texts of the remaining articles were then obtained and independently assessed by two reviewers with articles selected for exclusion agreed by both reviewers. Discrepancies were resolved by discussion.

Assessment of study validity

Paragraph Number 6 Included studies were assessed for methodological quality using the PEDro scale, which comprises 11 criteria of which the first determines external validity (eligibility criteria) and the remaining 10 measure internal validity (randomization, allocation concealment, homogeneity, subject, therapist and assessor blinded, <15% attrition of subjects, intention to treat, statistical comparison, measures of variability; for a detailed description of the PEDro scale and criteria see Maher et al. (64). The methodological quality of each study was established by awarding one point for each criterion satisfied with a total score out of 10. Two reviewers independently assessed the quality of studies, with disagreements resolved by discussion.

Data extraction

Paragraph Number 7 One reviewer extracted data from studies that met the inclusion criteria, whilst a second reviewer verified the validity of these data. Data that summarized the following factors were extracted: stretch duration, muscle group stretched, maximal muscular performance outcome measures, whether significance was or was not reached in each variable measured (within a realistic post-stretch timeframe, ≤ 20 min), mean reduction in a performance variable, and whether appropriate control or reliability analyses were reported. Where multiple variables were reported within studies, each relevant finding was included in the analysis to remove any possible bias on our part and to ensure that reporting bias was not introduced to the review. Multiple analyses within studies were grouped according to stretch duration, performance variable, contraction mode and muscle group. Where several significant or non-significant findings were reported within a specific grouping (for example concentric force at several velocities), only one of the significant or non-significant findings were tabulated for our synopsis, with the mean of the significant findings used for analysis.

This was done to ensure we did not inflate the importance of such studies in relation to others, and thus skew the analysis.

Data analysis

Paragraph Number 8 Two analyses are reported: 1) where all studies were included, in order to provide a holistic overview of the published literature, and 2) where studies without appropriate control or provision of reliability statistics were removed. This allowed us to determine whether the removal of studies based on experimental design influenced the findings of the review. Given the heterogeneity of intervention types (specifically differences in stretch duration and muscle group stretched), the diverse methods used to measure muscular performance (specifically isometric, concentric, eccentric or isokinetic muscle actions, drop-, countermovement- or squat-jump techniques, sprint running over various distances, free-weight or machine-based strength and power assessment) and that many studies failed to report specific statistical details of both their significant and non-significant findings, meta-analysis was deemed to be neither feasible nor appropriate (49). A systematic review of the literature was thus performed with studies pooled according to stretch-duration by examining the total time the muscle was placed under stretch (<30 s vs. 30-45 s vs. 1-2 min vs. >2 min) and examined for effects on performance in strength-, power- or speed-dependent tasks. Further analyses were performed again examining duration-dependent effects by muscle contraction mode (for example isometric vs. concentric vs. eccentric) and by muscle group stretched (lower-limb only; for example plantar flexors vs. knee extensors vs. knee flexors). The percentage of significant and non-significant findings and the magnitude of the changes in the performance variables were collated.

RESULTS

Search results

Paragraph Number 9 Our searches identified 4559 potentially relevant articles. By reviewing titles and abstracts we identified 112 articles examining the effects of acute static stretch on a maximal muscular performance variable, reference screening of these articles revealed a further 11 articles giving a total of 123 articles. After examining the full text, 17 articles were removed as they failed to meet our methodological inclusion criteria, which resulted in 106 articles being included for review (see Table, Supplemental Digital Content 1, which presents the major findings of the stretch-based studies included for review).

Methodological quality of included studies

Paragraph Number 10 Not all of the PEDro criteria could be satisfied as the experimental crossover design implemented by the majority of studies resulted in subject and therapist blinding not being possible. Given that therapist and assessor roles were normally performed by the same individuals, assessor blinding was also highly limited. Despite this limitation, the methodological quality of studies was found to be moderate, ranging from 3-7 (mean = 5.4 ± 0.9). The present review examined the study designs implemented from 106 RCT, Q-RCT and intervention-based studies. Careful examination of the study design revealed that 11 studies failed to include a control group or any reliability analyses and a further 21 inappropriately used a control condition (see Table, Supplemental Digital Content 1) that failed to determine reliability, which is a serious concern for the quality of their study design and validity of their data.

Overview - Effects on maximal muscular performance

Paragraph Number 11 Analysis of the 106 articles revealed that 55% had reported a significant reduction in performances in strength-, power- or speed-dependent tasks after acute static stretch, whilst 69% had reported no significant reduction in task performances. This apparent conflict in percentages can be explained by numerous studies reporting the effects of acute static stretch on several variables within the same study, including different muscle groups (12), muscle lengths (77), contraction modes (68), contraction velocities (78), durations of stretch (52, 58, 82, 96, 119), and performance tasks (91). In addition to equivocal data existing across studies, equivocal data also existed within 25 studies where significant and non-significant results were reported concurrently. By examining the findings within the studies rather than collating which studies report significant findings, we were able to remove the possibility of introducing reporting bias on our part. This approach yielded 149 findings from the 106 articles with only 44% of the findings indicating significant reductions in maximal strength-, power- or speed-dependent performance (pooled estimate of reductions = -3.7 ± 4.9%). When the studies without sufficient control or reliability were removed from the analysis, 74 studies reporting 104 findings remained. The percentage reporting significant reductions increased only slightly, to 50%, as a similar proportion of the studies removed reported significant and non-significant findings (pooled estimate of reductions = -4.5 ± 5.2%). Thus their removal did not markedly influence the results.

Dose-response relationship

Paragraph Number 12 To determine whether a dose-response effect of stretch was evident across the studies, we separated the research into groups where the total stretch duration imposed was either <30 s, 30-45 s, 1-2 min or >2 min (see Table 1). Surprisingly, only 10 studies reporting 11 findings were found that examined the effects of stretch where duration was <30 s. Nine studies did not reveal any significant reduction: five reported no change in power- or speed-dependent tasks including 20-m sprint time (8), vertical jump (19, 50, 75) and medicine ball throw (71), and two studies reported significant increases in 5-step jump distance (2.5% (71)) and peak cycling power (5% (81)), although this last study failed to demonstrate appropriate control. Furthermore, three studies reported no significant reductions in maximal strength, including isometric plantar flexor maximum voluntary contraction (MVC) (52), hand grip strength (58) or isometric and concentric knee extensor MVC (96). Only one study reported a significant, but small, reduction in 20-m sprint velocity (-1.2% (38)), which is in conflict with Beckett et al. (8). Collectively, the data from these studies demonstrate that short durations of stretch (<30 s) do not result in a meaningful reduction in muscular performance (pooled estimate = -1.1 ± 1.8%; see Figure 1).

Figure 1 here

Paragraph Number 13 When examining studies that employed a longer total duration of stretch (30-45 s), 25 studies were found reporting 31 findings. Fifteen studies examined power- or speed-dependent performance with only two studies reporting a significant reduction in vertical jump height (-4.2% (39); -4.3% (51)), although the latter study failed to demonstrate appropriate control. In direct conflict with these findings, nine studies reported no significant reduction in vertical jump performance (18, 31, 32, 42, 57, 62, 86, 103, 116) with one study reporting a significant increase in jump performance (2.3% (76)). Furthermore, no significant effect was detected for 10-m (62), 20-m (97) or 30-m (18) sprint time, with a significant improvement in 20-m rolling sprint time reported (1.7% (62)), which reinforces the previous suggestion that short-duration stretch does not clearly influence maximal running performance. Also, no significant reductions were reported for throwing velocity (44), bench press and overhead throws (101) or leg extension power (114). Collectively these data demonstrate no clear detrimental effect on performance in speed- and power-dependent tasks where stretch duration is 30-45 s (pooled estimate = -0.6 ± 3.1%; see Figure 1). This finding is especially important as the duration of stretch is reflective of normal pre-exercise routine practices (3, 98) and the performance tasks examined are highly applicable to both clinical and athletic subjects.

Table 1 here

Paragraph Number 14 Eleven studies examined the effects of 30-45 s of stretch on maximal strength, with equivocal findings being reported. Significant reductions were reported in hand grip strength (-7.8% (58); -6.7% (102)), concentric knee flexor MVC (-6.3% (110)) and isometric and concentric knee extensor MVC (-6.6% (96)). In contrast, three studies reported no significant effect on concentric knee extensor strength (9, 121, 122) following similar durations of stretch. Furthermore, no significant reductions were found in concentric plantar flexor MVC (2), chest press strength (9, 74) or isometric knee flexor MVC (82). Thus, while some studies have reported significant performance decrements in lower limb muscle groups, this is not a common finding. Overall, the majority of the findings suggest that no detrimental effect on strength is likely when stretch duration is 30-45 s (pooled estimate = -4.2 ± 2.7%; see Figure 1).

Paragraph Number 15 When stretch durations were greater, the percentage of significant losses reported increased sharply after 60-s of stretch (61%) and then reached a plateau when stretch duration increased above 2 min, indicating a sigmoidal relationship (see Figure 2). This finding is congruent with the previous dose-response studies (52, 58, 82, 96, 119).

Clearly the duration of stretch at which significant reductions are likely is approximately 60 s, however longer durations (>2 min) did not increase the likelihood of significant reductions further. A linear relationship was evident in the average magnitude of reductions as the average reductions continued to increase with longer durations of stretch (see Table 1).

Figure 2 here

Effect of contraction mode

Paragraph Number 16 Although the vast majority of findings from studies utilising shorter static stretch durations indicated no significant effect, equivocal findings were reported in studies using longer durations (≥60 s). Accordingly, we examined whether stretch duration influenced results when studies were organised by muscle contraction mode (see Table 1). Given that this reduced the sample size substantially, the four dose-response groups were merged into two (≤45 s & ≥60 s). A similar proportion of studies reported significant reductions after ≥60 s stretch in concentric and isometric strength (67% & 76% respectively), however the size of the reductions were greater for isometric than concentric (-8.9% & -5.2% respectively; see Table 1). The most interesting finding from this analysis was that only six of the 68 findings reported in studies examining the effect of contraction mode assessed changes in maximal eccentric strength (15, 27, 29, 69, 93, 111), and all of these used stretch durations >60 s. Two studies reported significant force losses (-4.3% (15); -9.7% (93)) while no change was reported in the remaining four studies that all used much longer stretch durations (3-9 min).

Muscle group-specific effects

Paragraph Number 17 A final analysis was conducted to determine whether the equivocal reports could be explained further by separating the studies by muscle group. The majority of studies focussed on lower limb strength with few studies examining upper body strength, accordingly studies measuring knee flexor, knee extensor and plantar flexor strength were examined; again the dose-response groups were merged into two groups (≤45 s & ≥60 s). While similar findings were revealed across muscle groups for magnitude of loss (see Table 1), the knee flexors (82%) appeared to be more regularly influenced by stretch compared to the knee extensors (64%) and plantar flexors (62%). This finding, in conjunction with the finding that the muscle contraction mode of the test exercise influenced the results, may partly explain the equivocal findings reported across the literature for longer duration (≥60 s) stretches. However, although there is some evidence for a contraction mode- and muscle-specific effect, the lack of data does not allow firm conclusions to be drawn and we cannot fully explain the equivocal findings reported for longer-duration stretches.

DISCUSSION

Paragraph Number 18 When all relevant studies are examined *in toto* the results of the present review appear to largely agree with previous suggestions that acute static stretching can reduce maximal muscle performance (63, 70, 89, 120). Forty-four percent of all variables included in our analyses (144 findings) from 106 studies showed significant reductions in maximal strength-, power- or speed-dependent performance. However, a more detailed examination reveals clear evidence that no performance decrements in strength-, power- or speed-dependent tasks occurs when total stretch durations are less than 45 s. Furthermore, there is only a moderate effect of stretch for durations greater than 60 s. We found there to be only minor differences in the effect across muscle contraction modes or muscle groups, and no substantial effect of movement velocity.

Potential bias

Paragraph Number 19 We used a systematic review methodology to remove potential sources of bias as far as possible, although this procedure does not guarantee the absence of bias. Analyses such as those performed in the present review may be influenced by publication bias (100) because studies reporting non-significant effects of stretch may have been less likely to be accepted for publication. However, the potential inclusion of these studies would not have changed the main conclusion that shorter-duration (≤45 s) stretching has no effect on force production. Examination of the methodological quality of the literature revealed experimental study design was often poor, where 30% of the studies reported no control group or reliability analyses. This supports the contention of Young (120), who previously highlighted this problem. Many studies did not include, or did not clearly report, a test reliability analysis, which is a major concern as it reduces the validity of the findings. Data presented in many of the included studies were collected during both control (rest) and experimental (stretch) conditions, and statistical analyses were then performed on the data sets to determine the level of significance between conditions. One problem, however, is that statistics for reliability were rarely presented so the potential exists for the magnitude of between-condition differences to have been within the limits of data variability, resulting from learning, motivation variability, fatigue or some other external influence, and were not solely influenced by the stretch intervention. Nonetheless, several statistical methods to eliminate this problem, including comparison of mean tests (for example t-tests, ANOVA), intraclass correlation coefficients (ICC) and coefficients of variation (CV) to establish reliability from repeated testing during control conditions, were appropriately used by several researchers (39, 107, 121) and should provide an exemplar for future research. Regardless, and importantly, our analysis revealed that the removal of studies with the poorer design did not markedly affect the conclusions drawn from the review because a similar proportion of these studies reported significant vs. non-significant results.

Acute effects of short-duration static stretch

Paragraph Number 20 The present systematic review revealed clear evidence that the widely reported negative effects of stretch on maximal strength performance are not apparent following stretch durations (≤30 s; 52, 58, 96) that are commonly performed in a pre-exercise routine (3, 98), although there are a limited number of studies imposing this stretch duration. Nonetheless, equivocal results were found when durations increased to 30-45 s in knee extensor (9, 96, 121, 122) and knee flexor MVC tests (82, 110). Significant reductions were found in hand grip strength (58, 102) but no change was found in plantar flexor MVC (2) or chest press one repetition maximum (9, 74). Examination of the literature revealed that while some studies have reported significant losses in lower limb muscle groups, others did not. Overall, 50% of the findings indicated that no detrimental effect on strength was likely when stretch duration was 30-45 s, with the pooled estimate of the changes (-4.2 ± 2.7%) well within the normal variability for maximum voluntary performance.

Paragraph Number 21 There was also clear evidence that stretch did not affect higher-speed force production when stretch durations were ≤45 s. Only two studies reported significant decreases in vertical jump height (39, 51), with the latter failing to use an appropriate control. In direct conflict were 13 studies employing similar durations of stretch that reported no significant reduction in jump performance (18, 19, 31, 32, 42, 50, 57, 62, 75, 76, 86, 103, 116). Similar patterns were evident in sprint performance where again only one study reported a significant reduction (38), whilst four studies reported no significant reduction (8, 18, 62, 97), and Little & Williams (62) reported an increase in sprint performance. Interestingly, Fletcher & Jones (38) did not employ a control condition but determined reliability with ICC and CV calculations. The CV was calculated at 1.7%, which was greater than the significant difference reported; the standard error of the mean was also a similar size to the reduction reported, and the effect size calculated from the reduction was small. While the study design and implementation of statistics was correct, the interpretation of their data and practical importance of the finding are debatable. Only two studies that demonstrated appropriate control or reliability reported a significant reduction in performance, as opposed to 15 that reported no difference in the same tasks and a further five studies reporting no difference in performance in other speed or power tests (44, 71, 81, 101, 114). Collectively, these data overwhelmingly indicate that there is no detrimental effect of short-duration static muscle stretch on speed- or power-dependent performance, with the pooled estimate of the change calculated at -0.5 ± 2.8%.

Dose-response effects of stretch

Paragraph Number 22 The lack of consensus regarding the negative effects of static stretching is likely to be partly attributable differences in the durations of stretch imposed across studies. Short-duration stretching tends not to result in significant impairments whereas longer stretch duration more likely does, with the percentage of significant findings increasing concurrently with stretch duration (<30 s = 14%; 30-45 s = 22%; 1-2 min = 61%; >2 min = 63%). This is in agreement with several recent studies (52, 58, 82, 90, 96, 119) that specifically examined the dose-response effect of static muscle stretch on active force production. For example, Ogura et al. (82) reported that 30 s of stretch did not reduce isometric knee flexor strength but that 60 s of stretch induced significant impairment, and

Knudson and Noffal (58) found that repeated 10 s stretches did not reduce hand grip strength compared to control until 40 s of total stretch was accumulated. Similarly, 5, 15 and 20 s of static stretch did not significantly reduce isometric plantar flexor force while 60 s of stretch did (52); the size of the force impairment was also significantly correlated with the stretch duration, clearly highlighting the importance of stretch duration in the magnitude of force loss. Those studies, and other evidence reported in the present review, indicate that a clear dose-response effect exists with decrements becoming more likely for stretch durations ≥60 s but not continuing to increase beyond 2 min. Thus the dose-response relationship appears to be sigmoidal, with turning points at approximately 60 s and 2 min (see Figure 2).

Paragraph Number 23 Interestingly, comparable dose-response trends were evident across tasks involving largely strength-, power- or speed-dependent movements, which suggest that the effects of stretch duration are task independent. However, the number (percentage) of significant findings and the magnitude of the performance decrement were larger for strength-based than power- and speed-based tasks. Given that power- and speed-dependent tasks are more typically performed in activities of daily living or athletic pursuits than the laboratory-based slow-speed strength tests, these findings perhaps have more practical relevance. Regardless, the finding that short-duration stretches (≤45 s) did not appear to impair muscle force production is of even greater practical importance. This important finding suggests that static muscle stretching can be safely used in a pre-exercise routine without compromising physical performance, whereas longer durations (≥60 s) are more likely to be problematic. While the majority of short duration studies (≤45 s) revealed no significant change, significant improvements were reported in jumping (71, 76), cycling (81) and sprinting (62) performances, which suggest that improvements are possible in some tasks. Furthermore, significant improvements in range of motion and reduced musculotendinous stiffness following short-duration stretches (5-30 s) have also been reported (7, 52) that may reduce muscle strain injury risk. Thus, the inclusion of short-duration pre-performance stretching may be deemed useful by some practitioners, although more research is needed to clarify the effects of short duration static stretching.

Paragraph Number 24 While a similar influence was seen across muscle groups (lower limb) and contraction modes, no studies exist detailing the effects of moderate-duration stretches (≤45 s) on eccentric strength. This is important not only for its physical performance implications but because of its impact on injury risk. Muscle strength has been cited as a major influencing factor within the aetiology of muscle strain injury (83), and, with most muscle strain injuries suggested to occur within normal range of motion (ROM) during eccentric loading, the ability of the muscle to withstand eccentric loading may be crucial to injury risk. Given the equivocal data reported from much longer durations of stretch (for example >60 s) on eccentric strength, and that there are presently no data describing the effects of shorter, more practically relevant, stretch durations (≤45 s), a clear research focus is needed to fully explore the influence of stretch on the muscle's ability to withstand eccentric loading.

CONCLUSIONS

Paragraph Number 25 Static muscle stretches totalling less than 45 s can be used in pre-exercise routines without risk of significant decreases in strength-, power- or speed-dependent task performances. Longer stretch durations (for example ≥60 s) are more likely to cause a small or moderate reduction in performance. Interestingly, the effect of stretch on performances across a range of muscle contraction modes, muscle groups and movement speeds were similar. Importantly, no studies exist detailing the effects of moderate-duration stretches (≤45 s) on eccentric strength and there is little evidence for an effect after longer periods of stretch. This is important because the purported influence of eccentric strength on both movement performance and injury risk. Several avenues of further research exist, including an examination of the effects of stretch on upper body musculature and on eccentric movement performance, and more data are required to determine the effect of short-duration stretches (≤30 s) in order to more clearly delineate the magnitude of effect. A comprehensive review of the existing literature examining the influence of other forms of muscle stretching (dynamic, PNF and ballistic) should also be performed as the effects of different stretching modalities are likely to be different. Finally, no attempt was made in the present review to determine whether the number of stretches performed, in addition to the total duration of stretch, is a factor influencing the effects of stretch, so future reviews are required to clarify whether it is a factor influencing the stretch-induced loss of force.

Contributors: AK performed the literature search, selected articles for exclusion and inclusion, assessed the risk of bias, extracted the data, and performed the analysis. AB verified a percentage of articles selected for exclusion, verified all articles selected for inclusion, verified the extracted data, and assessed the risk of bias. All authors were involved in the study design, contributed to the writing and revision of the manuscript and are able to take responsibility for its accuracy.

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Supplemental Digital Content 1. Table that presents the major findings of the stretch-based studies included for review. pdf

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TABLES & FIGURES

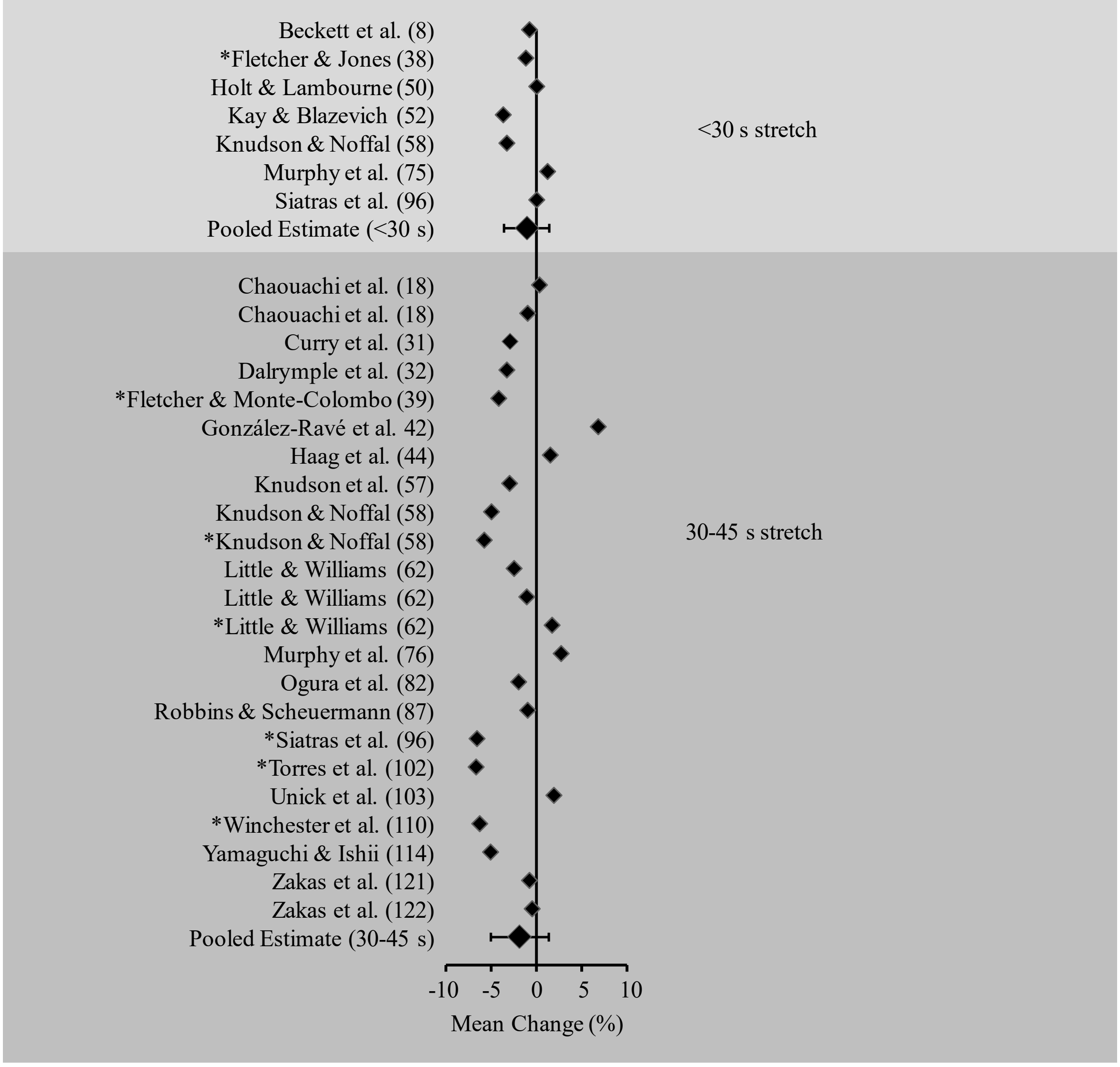

Figure 1. Mean percentage change (*significant; $p < 0.05$) in strength-, power- and speed dependent task performance following stretches of <30 s (top panel) or 30-45 s (bottom panel) duration. The majority of studies found no significant reduction in muscle performance following shorter stretch durations with small mean reductions calculated across studies indicating no meaningful change in performance.

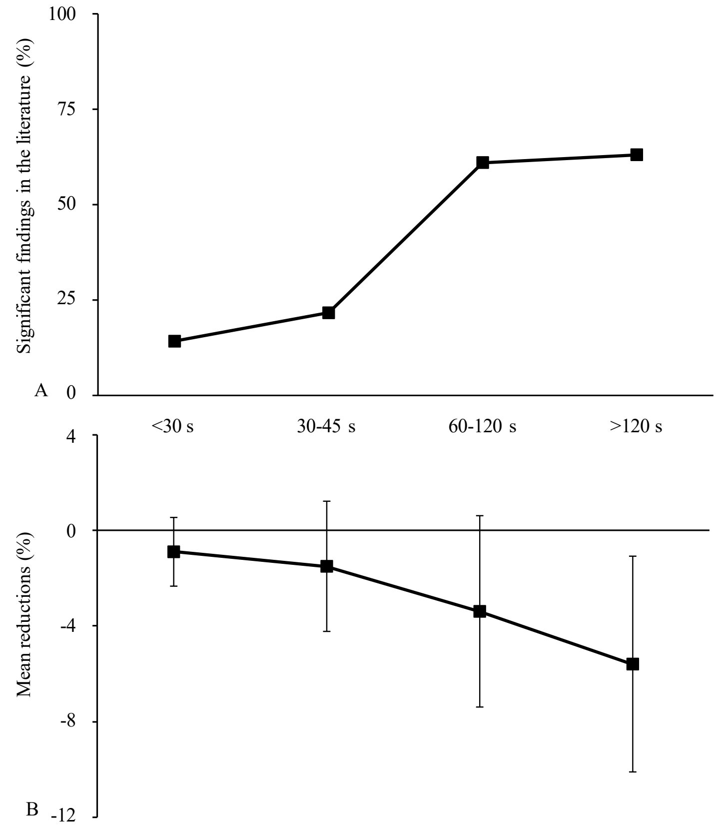

Figure 2. The sigmoidal relationship between (A) stretch duration and likelihood of a significant reduction, and (B) curvilinear relationship between stretch duration and the mean reduction in the performance of strength-, power- and speed-dependent tasks. The likelihood of significant reductions was minimal following stretch durations of <30 s (14%) and 30-45 s (22%); this rose sharply following 1-2 min (61%) then reached a plateau after >2 min (63%) of stretch. The average magnitude of losses also remained small for shorter duration stretches (pooled estimate <30 s = -1.1 ± 1.8%; 30-45 s = -1.9 ± 3.4), then continued to increase with longer durations of stretch (pooled estimate 1-2 min = -4.2 ± 5.0%; >2 min = -7.0 ± 5.7).

Table 1. Effects of static stretch on muscular performance.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
#Alpkaya & Koceja (2)	PF	3×15	15	No sig diff in concentric PF force (-3.5%)
Babault et al. (4)	PF	20×30	10	Sig ↓ in isometric PF (-6.9%)
Bacurau et al. (5)	KE, KF	9×30	14	Sig ↓ in leg press maximal strength (-13.4%)
#Bazett-Jones et al.(6)	KE, KF, HF, HE	3×30	10	No sig diff in isometric squat force (+1.2%)
Beckett et al. (9)	KE, KF, PF, HF, HA	20	12	No sig diff in 20 m sprint time (-0.8%)
#Beedle et al. (9)	KE, KF, PM, D, TB	3×15	51	No sig diff in chest (-0.5%) or leg press 1RM (-1.3%)
Behm et al. (10)	KE	5×45	12	Sig ↓ in isometric KE MVC (-12.2%)
Behm et al. (11)	KE, KF, PF	3×45	16	No sig diff in isometric leg extensor MVC (-6.9%)
Behm et al. (12)	KE, KF, PF	3×30	18	Sig ↓ in isometric KE (-8.2%) & KF (-6.6%) MVC, and in CMJ height (-5.7%); no sig diff in DJ (0%)
Behm & Kibele (13)	KE, KF, PF	4×30	10	Sig ↓ in DJ (-5.3%), SJ (-3.8%) and CMJ (-5.6%)
Bradley et al. (14)	KE, KF, PF	4×30	18	Sig ↓ in CMJ (-4%)
Brandenburg (15)	KF	6×15, 6×30	16	Sig ↓ in isometric (90 s = -6.7%; 180 s = -6.1%), isokinetic concentric (90 s = -2.7%; 180 s = -3.3%), and eccentric KF MVC (90 s = -2.6%; 180 s = -4.5%) at 120°·s^{-1}
Brandenburg et al. (16)	KE, KF, PF	3×30	16	No sig diff in CMJ height (-3%)
Burkett et al. (17)	KE, KF, HA, PF	3×20	29	No sig diff in CMJ height (+0.7%)
Chaouachi et al. (18)	KE, KF PF, HE, HA	30	22	No sig diff in CMJ height (+0.3%) or 30 m sprint (-1%)

Table 1. Cont.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
#Church et al. (19)	KE, KF	15	40	No sig diff in CMJ height (-1.2%)
#Cornwell et al. (20)	KE	3×30	10	Sig diff in CMJ (-4.3%) and SJ (-4.4%) height
†Cornwell et al. (21)	PF	6×30	10	Sig ↓ in CMJ (-7.4%), no sig diff in SJ height (0%)
Costa et al. (22)	PM, TB	9×20	20	Sig ↓ in bench press MVC (-8.8%)
†Costa et al. (23)	KF, PF	16×30	13	Sig ↓ isokinetic concentric KF MVC at 60°·s^{-1} (-9.3%), 180°·s^{-1} (-2.8%) and 300°·s^{-1} (-8.8%)
†Costa et al. (24)	KF, PF	16×30	15	No sig diff in isokinetic concentric KF MVC at 60°·s^{-1} (+1.1%), 180°·s^{-1} (-0.6%) and 300°·s^{-1} (-2.5%)
Cramer et al. (25)	KE	16×30	14	No sig ↓ in isokinetic concentric KE MVC at 60°·s^{-1} and 240°·s^{-1} (mean = -2.3%)
Cramer et al. (26)	KE	16×30	21	No sig ↓ in isokinetic concentric KE MVC at 60°·s^{-1} and 240°·s^{-1} (mean = -3.5%)
Cramer et al. (27)	KE	16×30	13	No sig ↓ in isokinetic eccentric KE MVC at 60°·s^{-1} or 240°·s^{-1} (mean = -3.8%)
Cramer et al. (28)	KE	16×30	18	Sig ↓ in isokinetic concentric KE MVC (-3.1%)
Cramer et al. (29)	KE	16×30	15	No Sig ↓ in isokinetic eccentric KE MVC at 60°·s^{-1} or 240°·s^{-1} (mean = -0.7%)
Cronin et al. (30)	KF	3×30	10	No Sig ↓ in CMJ height (0%)

Table 1. Cont.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
Curry et al. (31)	HE, HF, KE, KF, PF	3×12	24	No Sig ↓ in CMJ height (-2.9%)
Dalrymple et al. (32)	KE, KF, HE, PF	3×15	12	No Sig ↓ in CMJ height (-3.3%)
Di Cagno et al. (33)	KE, KF, PF	3×30	38	No Sig ↓ in CMJ (0%) or SJ (0%) flight time
Egan et al. (34)	KE	16×30	11	No Sig diff in isokinetic concentric KE MVC at $60°·s^{-1}$ or $240°·s^{-1}$ (mean = -0.2%)
Evetovich et al. (35)	BB	16×30	18	Sig ↓ in isokinetic concentric elbow flexor MVC at $30°·s^{-1}$ & $270°·s^{-1}$ (mean = -4.6%)
Evetovich et al. (36)	KE	16×30	29	Sig ↓ in isokinetic concentric leg extensor MVC at $60°·s^{-1}$ & $300°·s^{-1}$ (mean = -6%)
Favero et al. (37)	HE, KE, KF, PF	2×45	10	No sig diff in 40 m sprint (0%)
Fletcher & Jones (38)	HE, HF, HA, KE, KF, PF	20	28	Sig ↓ in 20 m sprint velocity (-1.2%)
Fletcher & Monte-Colombo (39)	HE, HF, KE, KF, PF	2×15	21	Sig diff in CMJ (-3.4%) and DJ (-4.9%)
Fowles et al. (40)	Sol	13×135	10	Sig ↓ in isometric PF MVC (-28%)
†Gavin & Morse (41)	PF	5×60	10	Sig ↑ in isometric PF MVC (2.9%)
González-Ravé et al. (42)	KE, KF, PF	3×15	24	No sig diff in SJ or CMJ height (+6.8%)
Gurjão et al. (43)	KE, KF, HE, HA	3×30	23	Sig diff in isometric KE MVC (-5.2%) compared to control

Table 1. Cont.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
Haag et al. (44)	SM	30	12	No sig diff in throwing velocity compared to control condition (+1.5%)
#Handrakis et al. (45)	HE, KE, KF, PF	3×30	10	No sig diff in standing broad jump and single leg hop compared to control condition (-2%)
Herda et al. (46)	KF	12×30	14	Sig ↓ in isometric KF MVC at 81° (-7.2%) & 101° (-15.9%), no sig diff at 41° & 61°, (mean = -11.6%)
Herda et al. (47)	PF	9×135	15	Sig ↓ in isometric PF MVC (-10%)
Herda et al. (48)	PF	9×135	11	Sig ↓ in isometric PF MVC (-11%)
Holt & Lambourne (50)	ES, HE, HF, KE, KF	3×5	21	No sig diff in CMJ height (0%)
#Hough et al. (51)	HE, HF, KE, KF, PF	30	11	Sig diff in SJ height (-4.2%)
Kay & Blazevich (52)	PF	5, 15, 4×5, 4×15	7	Sig ↓ in isometric PF MVC (-16.7%) after 60-s, no change after shorter durations
Kay & Blazevich (53)	PF	3×60	15	Sig ↓ in concentric PF MVC (-5%)
Kay & Blazevich (54)	PF	3×60	16	No change in concentric PF MVC when stretch follows isometric contractions
Kay & Blazevich (55)	PF	3×60	18	Sig ↓ in concentric MVC at 90% ROM only (-5.8%)
Kistler et al. (56)	KE, HF, KF, PF	3×30	18	No sig diff in 0-20m, 40-60m, 80-100m sprint times (mean = -0.3%), a Sig ↓ at 20-40m (-1.4%)
Knudson et al. (57)	KE, KF, PF	3×15	20	No sig diff in vertical velocity compared to control condition (-3%)

Table 1. Cont.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
Knudson & Noffal (58)	WF	10×10	35	Sig ↓ in hand grip strength (-5.8%) compared to control after 40 s, no sig diff after shorter durations
#Kokkonen et al. (59)	HE, KE, KF, PF	6×15	30	Sig ↓ in concentric KF MVC (-7.3%) & concentric KE MVC (-8.1%)
†Kubo et al. (60)	PF	10 min	7	No change in isometric PF MVC (-1.9%)
La Torre et al. (61)	KE, PF	4×30	17	No sig diff in SJ height (-2.6%), at 110°, 90° and 70° starting knee position, Sig ↓ at 50° (-20.8%)
Little & Williams (62)	HE, HF, HA, KE, KF, PF	30	18	No sig diff in CMJ height (-2.5%), 10 m sprint (-1.1%), sig faster rolling 20 m sprint (+1.7%)
†Maisetti et al. (65)	PF	5×15	11	Sig ↓ in isometric PF MVC (-10%)
Manoel et al. (66)	KE	3×30	12	No sig change in concentric KE force at 60°.s-1 or 180°.s-1 (mean = -2.8%)
†Marek et al. (67)	KE	16×30	19	No sig ↓ in isokinetic concentric KE force 60°.s-1 or 300°.s-1 (mean = -1%)
McBride et al. (68)	KE	9×30	8	Sig ↓ in isometric KE (-19.3%), no Sig ↓ in isometric squat (-8%) compared to control
†McHugh & Nesse (69)	KF	6×90	10	Sig ↓ in isometric KF (-7%), no diff in isokinetic concentric (+1.1%) or eccentric (-1.4%) at 60°.s-1

Table 1. Cont.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
#McMillian et al. (71)	ES, HE, HF, KE, KF, PF	20	30	No sig diff in medicine ball throw (-1.4%) and sig better 5-step distance (+2.8%)
McNeal & Sands (72)	PF, KF	3×30, 2×30	13	Sig diff in flight time for drop jump (-9.6%) compared to control condition
#Molacek et al. (74)	PM, TB	2×20, 5×30	15	No sig diff in 1RM bench press after 40 s (0%) and 2.5 min (-1.2%)
Murphy et al. (75)	HE, HF, HA, KE, KF, PF	20	14	No sig diff in CMJ height (1.2%)
Murphy et al. (76)	KE, KF, PF	6×6	14	Sig ↑ in CMJ height (2.7%)
†Nelson et al. (77)	KE	8×30	55	No sig diff in isometric KE MVC at 90°, 108°,126° & 144°, Sig ↓ in MVC (-7%) at 162°
†Nelson et al. (78)	KE	16×30	15	No sig diff at 3 faster velocities, sig ↓ in concentric KE MVC at 1.05 (-7.2%) & 1.57 rad.s-1 (-4.5%)
Nelson et al. (79)	KE, KF, PF	4×30	16	Sig ↑ in 20 m sprint time (+1.3%)
#Nelson et al. (80)	KE, KF	6×15	31	Sig diff in concentric KF MVC (-3.6%) & concentric KE MVC (-5.7%) compared to control
#O'Connor et al. (81)	HE, HF, HA, KE, KF, PF	2×10	27	Sig diff (↑) in peak cycling power (+5%)

Table 1. Cont.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
Ogura et al. (82)	KF	30, 60	10	Sig diff in isometric KF MVC (-8.8%) after 60 s but no sig diff after 30 s (-2%)
Papadopoulos et al. (84)	KE, KF	3×30	32	Sig diff in isokinetic concentric KE MVC (-4.3% and -4.4%) and KF MVC (-5% and -4.3%) at 60°·s^{-1} and at 180°·s^{-1} (mean = -4.5%)
#Papadopoulos et al. (85)	KE, KF, PF	9×30	10	No sig diff in isometric KE MVC (-1%) compared to control
Power et al. (86)	KE, PF	6×45	12	Sig diff in isometric KE MVC (-9.5%), no sig diff in PF MVC (0%), SJ or DJ height (0%)
Robbins & Scheuermann (87)	KE, KF, PF	2×15, 4×15, 6×15	20	Sig ↓ in CMJ after 90 s stretch only (-3.2%) no Sig ↓ in shorter durations (30 s = -1%; 60 s = -2.2%)
Rossi et al. (88)	KE	6×30,6×60	20	Sig ↓ in isometric KE MVC (3 min - 4%; 6 min - 8%)
Ryan et al. (90)	PF	4×30, 8×30, 16×30	13	No Sig ↓ in isometric PF MVC after 2 min (-2%) or 4 min (4%) or 6 min (6%) compared to control condition
#Samuel et al. (91)	KE, KF,	3×30	24	No sig diff in CMJ height, isokinetic concentric KE or KF MVC at 60°·s^{-1}. Sig diff in power (-3.5%)
Sayers et al. (92)	KE, KF, PF	3×30	20	Sig diff in 30-m sprint time (-2%) compared to control
Sekir et al. (93)	KE, KF,	4×20	10	Sig ↓ in concentric KE MVC at 60°·s^{-1} (-6.7%) & 180°·s^{-1} (-9%), KF at 60°·s^{-1} (-8%) & 180°·s^{-1} (-8%); in eccentric KE at 60°·s^{-1} (-9.9%) & 180°·s^{-1} (-9.9%) & KF at 60°·s^{-1} (-11.9%) & 180°·s^{-1} (-13.9%)

Table 1. Cont.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
#Siatras et al. (95)	KE, KF, PF	2×30	11	Sig diff in running speed (-3%) compared to control condition after 10 m and 15 m but not after 5 m
Siatras et al. (96)	KE	10, 20, 30, 60	10	Sig ↓ in isometric (30 s - 8.5%; 60 s - 16%) and isokinetic concentric KE MVC (30 s - 5.5%; 60 s - 11.6%) at $60°\cdot s^{-1}$ (30 s – 5.8%; 60 s - 10%) at $180°\cdot s^{-1}$. No sig diff after 10 s or 20 s stretch
#Sim et al. (97)	KE, KF, PF	2×20	13	No sig diff in 20 m sprint time (-1%) compared to control
#Torres et al. (101)	D, Tr, TB, BB, PM, LD	2×15	11	No sig diff in isometric bench press (3.2%), bench press throw (2.2%) or overhead throw (1%) compared to control
Torres et al. (102)	WF	3×10	15	Sig ↓ in hand grip MVC (-6.7%)
Unick et al. (103)	KE, KF, PF	3×15	16	No difference in SJ (+2.3%) or CMJ (+1.4%) compared to control condition
Vetter (104)	HE, KE, KF, PF	2×30	26	Sig diff in CMJ height (-0.8%); no sig diff in 30 m sprint time (-1.0%)
Viale et al. (105)	KE	9×45	8	Sig ↓ in (-8%) isometric KE MVC
†Wallmann et al. (106)	PF	3×30	14	Sig ↓ in CMJ height (-5.6%)
Wallmann et al. (107)	PF	3×30	13	No Sig ↓ in CMJ height (+2.9%)
Weir et al. (108)	Sol	5×120	15	Sig ↓ in isometric PF MVC (-7.1%)
Winchester et al. (109)	HE, KE, KF, PF	3×30 s	22	Sig diff in 40 m sprint time (-1.7%) but no difference for 20 m sprint time (-1%) compared to control.

Table 1. Cont.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
Winchester et al. (110)	KF	30, 2×30, 3×30, 4×30, 5×30	18	Sig diff in concentric KF MVC after 30 s (-6.3%), 60 s (-5.7%), 90 s (-7.9%), 120 s (-10.2%), 150 s (-11.1%) and 180 s (-12.1%) (mean = -8.9%) compared to control
Winke et al. (111)	KF	6×30	29	No sig ↓ in concentric KF MVC at 60°·s^{-1} (-7.7%) & 210°·s^{-1} (-6.9%) or eccentric KF at 60°·s^{-1} (-17.1%) & 210°·s^{-1} (-14.3%) compared to control
Yamaguchi & Ishii (114)	HF, HE,KE, KF, PF	30	11	No Sig ↓ in leg extension power (-5.1%)
Yamaguchi et al. (115)	KE	24×30	12	Sig diff concentric peak power (9%)
#Young & Elliott (116)	HEs, KE, PF	3×15	14	No sig diff in SJ height (-1.9%)
#Young & Behm (117)	KE, PF	4×30	16	No sig diff in SJ (-3.4%) or DJ (-3%) height compared to control
#Young et al. (118)	KE, HFs	9×30	16	No sig diff in foot speed (+0.5%)
#Young et al. (119)	PF	2×30, 4×30, 8×30	20	No sig diff in concentric PF peak force (-0.3%; -3%; -3.4%) or DJ height (-1.7%; -3.6%; -6.1%) after 1 min, 2min, or 4 min respectively
Zakas et al. (121)	KE	3×15, 20×15	16	No ↓ in isokinetic concentric KE MVC after 45 s (mean = -0.8%). Sig ↓ after 5 min stretch at 30°·s^{-1} (-5.2%), 60°·s^{-1} (-5.8%), 120°·s^{-1} (-6.5%), 180°·s^{-1} (-8.4%) and at 300°·s^{-1} (-12.9%)

Table 1. Cont.

Authors	Muscle group/s	Stretch duration (s)	Sample	Major findings
Zakas et al. (122)	KE	30 ,10×30, 16×30	14	No ↓ in isokinetic concentric KE torque after 30 s stretch (-0.5%). Sig ↓ after 5 and 8 min stretch at 60°·s^{-1} (-3.8% & -5.4%), 90°·s^{-1} (-4.9% & -6%), 150°·s^{-1} (-5.6% & -7.1%), 210°·s^{-1} (-5.3% & -7%) and at 270°·s^{-1} (-9.1% & -8.8%) respectively
Zakas et al. (123)	KE	4×15, 32×15	15	No change in isokinetic concentric KE torque after 60 s stretch (-0.3%). Sig ↓ after 8 min stretch at 60°·s^{-1} (-5.5%), 90°·s^{-1} (-5.9%), 150°·s^{-1} (-7.2%), 210°·s^{-1} (-6.6%) and 270°·s^{-1} (-8.2%) respectively

PF = Plantar flexor, Sol = soleus, HF = hip flexor, HE = hip extensor, HA = hip adductor, KE = knee extensor, KF = knee flexor, PM = pectoralis major, D = deltoids, Tr = trapezius, LD = latissimus dorsi, TB = triceps brachii, BB = biceps brachii, WF = wrist flexors, ES = erector spinae, SM = shoulder musculature, Sig diff = significant difference compared to control, ↑ = increase, ↓ = decrease, # = Control condition included but no reliability data, † = No control group