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REVIEW

Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review

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Abstract: Recently, there has been a shift from static stretching (SS) or proprioceptive neuromuscular facilitation (PNF) stretching within a warm-up to a greater emphasis on dynamic stretching (DS). The objective of this review was to compare the effects of SS, DS, and PNF on performance, range of motion (ROM), and injury prevention. The data indicated that SS- (–3.7%), DS- (+1.3%), and PNF- (–4.4%) induced performance changes were small to moderate with testing performed immediately after stretching, possibly because of reduced muscle activation after SS and PNF. A dose–response relationship illustrated greater performance deficits with ≥60 s (–4.6%) than with <60 s (–1.1%) SS per muscle group. Conversely, SS demonstrated a moderate (2.2%) performance benefit at longer muscle lengths. Testing was performed on average 3–5 min after stretching, and most studies did not include poststretching dynamic activities; when these activities were included, no clear performance effect was observed. DS produced small-to-moderate performance improvements when completed within minutes of physical activity. SS and PNF stretching had no clear effect on all-cause or overuse injuries; no data are available for DS. All forms of training induced ROM improvements, typically lasting <30 min. Changes may result from acute reductions in muscle and tendon stiffness or from neural adaptations causing an improved stretch tolerance. Considering the small-to-moderate changes *immediately* after stretching and the study limitations, stretching within a warm-up that includes *additional* poststretching dynamic activity is recommended for reducing muscle injuries and increasing joint ROM with inconsequential effects on subsequent athletic performance.

Key words: static stretch, dynamic stretch, proprioceptive neuromuscular facilitation, ballistic stretch, flexibility, warm-up.

Résumé : Depuis peu, on utilise plutôt l'étirement dynamique (« DS ») que l'étirement statique (« SS ») ou la facilitation neuromusculaire proprioceptive (« PNF ») au sein d'une séance d'échauffement. Cette analyse documentaire se propose de comparer les effets de SS, DS et PNF sur la performance, l'amplitude de mouvement (« ROM ») et la prévention de blessures. D'après les données, on observe des modifications de performance faibles à modérées quand l'évaluation est réalisée immédiatement après la séance d'étirement : SS (–3,7 %), DS (+1,3 %) et PNF (–4,4 %), et ce, possiblement à cause de la diminution de l'activation musculaire consécutive à SS et PNF. La relation dose-réponse révèle une plus grande baisse de performance quand la séance de SS par groupe musculaire ≥60 s (–4,6 %) vs. <60 s (–1,1 %). Par contre, SS suscite un gain modéré de performance (2,2 %) quand le muscle est plus allongé. L'évaluation est réalisée en moyenne 3-5 minutes post-étirement. La plupart des études n'incluent pas des activités dynamiques post-étirement; avec l'inclusion de ces activités, on n'observe pas de modification nette de la performance. DS suscite des gains de performance faibles à modérés quand la séance est effectuée dans les minutes suivant l'activité. SS et PNF n'ont pas d'effet clair sur les blessures dues au surmenage ou toutes causes confondues; il n'y a pas de données au sujet de DS. Tous les types d'entraînement, notamment ceux <30 min présentent des gains de ROM. Les modifications dépendent peut-être de la diminution ponctuelle de la rigidité tendineuse et musculaire ou d'adaptations nerveuses causant une plus grande tolérance à l'étirement. Compte tenu des modifications faibles à modérées *immédiatement* après la séance d'étirement et des limites des études, l'inclusion des étirements au sein d'une séance d'échauffement comportant *l'ajout* d'activités dynamiques post-étirement est recommandée pour diminuer les blessures musculaires et accroître ROM articulaire sans conséquence sur la performance physique subséquente. [Traduit par la Rédaction]

Mots-clés : étirement statique, étirement dynamique, facilitation neuromusculaire proprioceptive, étirement balistique, flexibilité, échauffement.

Introduction

The conventional' preactivity routine consists of a submaximal exercise component (e.g., running, cycling), a bout of muscle stretching in which muscles are held in an elongated position for 12–60 s (Ebben et al. 2004; Simenz et al. 2005), and a segment of skill rehearsal (specific warm-up) in which the individuals perform dynamic movements similar to those of the sport or event (Young 2007). Static stretching (SS) is considered an effective method for increasing joint range of motion (ROM) (Paradisis et al. 2014; Power et al. 2004) and is often thought to improve performance (Young and Behm 2003; Young 2007) and reduce the incidence of activity-related injuries (Ekstrand et al. 1983; Hadala and

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Barrios 2009). It is therefore commonly performed in preactivity routines (Ebben et al. 2005; Simenz et al. 2005). However, recent evidence suggests that sustained SS could impair subsequent performance (Shrier 2004; Behm and Chaouachi 2011; Kay and Blazevich 2012), and the perceptions regarding the benefits of SS in a preactivity routine have changed dramatically. Indeed, the current evidence indicates significant positive effects of dynamic forms of stretching (DS). There is also debate as to the benefits of preactivity stretching with respect to changes in ROM and injury risk.

Prior reviews have examined SS (Kay and Blazevich 2012), or SS and DS (Behm and Chaouachi 2011), but no reviews have comprehensively investigated the effects of preactivity SS, DS, and proprioceptive neuromuscular facilitation (PNF) on subsequent performance, ROM, and injury incidence. Furthermore, many additional studies have been published since these reviews. In this review, we provide an overview of the literature citing the effects of preactivity stretching on physical performance, injury risk, and ROM, as well as the physiological mechanisms, with the objective of investigating, analyzing, and interpreting the acute physical responses to a variety of stretching techniques to provide clarity regarding the impact on performance, ROM, and injury.

Materials and methods

Search strategy

This review included studies that examined the acute effects of SS, DS, and PNF stretching on physical performance, ROM, and injury incidence. A literature search was performed independently by the 4 authors using MEDLINE, SPORT Discus, ScienceDirect, Web of Science, and Google Scholar databases using a number of key terms: static, dynamic, ballistic stretching, PNF, flexibility, warm-up, prior exercise, performance, injury, and acute effects. These key words were used individually and/or were combined. All references from the selected articles were also cross-checked by the authors to identify relevant studies that may have been missed in the search.

Inclusion criteria

Studies examining the acute effects of muscle stretching on ROM and functional performance were included in the review if they fulfilled the following selection criteria: (*i*) the study contained research questions relating to the effect of SS, DS, and/or PNF stretching on performance, ROM, and injury and used (*ii*) healthy and active human subjects (senior adult studies excluded); (*iii*) the outcome was a physiological or performance measure; and (*iv*) the study was an English language study written between 1989 (first paper to report poststretch force impairments) and 2014 and published as an article in a peer-reviewed journal or conference proceeding (abstracts and unpublished studies were excluded). The exclusion of non-English articles is a limitation of this review. Furthermore, studies were delineated with respect to their internal validity. Selection criteria included studies involving (*i*) a control group, (*ii*) randomized control, and (*iii*) instruments with high reliability and validity. Studies reporting the effects of preactivity muscle stretching on joint ROM and injury incidence were also examined, without the above criteria being adhered to (some omissions were made, and these are described in the text).

Mean changes in performance were noted for each study, and the weighted means (i.e., means adjusted relative to study sample size) and 95% confidence intervals (CIs) were determined. Based on the prevalence of different magnitudes of change reported in the literature and an estimated smallest worthwhile change of 0.5%, we refer to changes of <0.5% as trivial, 0.5%–<2% as small, 2%–<5% as moderate, 5%–10% as large, and >10% as very large (Hopkins 2004). Effect sizes (ES) describing the magnitude of the differences between groups or experimental conditions (Cohen 1988) were calculated for each study for which absolute mean data and SD statistics were provided; weighted ES and 95% CIs were then determined. Cohen (1988) described ES <0.2 as representing a trivial, 0.2–0.39 as a small, 0.4–0.69 as a moderate, and ≥0.7 as a large magnitude of change.

Acute effects of muscle stretching

Static stretching

SS involves lengthening a muscle until either a stretch sensation (Cronin et al. 2008) or the point of discomfort is reached (Behm et al. 2004) and then holding the muscle in a lengthened position for a prescribed period of time (Ebben et al. 2004). SS is commonly used in clinical and athletic environments with the specific aims of increasing joint ROM and reducing injury risk (McHugh and Cosgrave 2010). However, a growing body of research has reported negative effects of SS on maximal muscular performance. Although early reviews accessed relatively few studies and reported equivocal findings (Rubini et al. 2007; Shrier 2004; Young 2007), more recent reviews encompassing a broader body of work have highlighted a clear dose–response effect in which longer stretch durations (e.g., ≥60 s) likely elicit performance impairments (Behm and Chaouachi 2011; Kay and Blazevich 2012), which may have important implications for athletic and clinical performance.

The largest systematic review to date (Kay and Blazevich 2012) examined 106 SS studies; our searches found a further 19 studies since 2011 that met our criteria, resulting in 125 studies incorporating 270 maximal performance measures (Table 1, Supplementary Table S1[1] and Supplementary Fig. S1*a*[1]) examining the acute effects of SS on performance (e.g., vertical jump height, sprint running time, chest and bench press 1-repetition maximum (1-RM), and maximal voluntary contractions (MVC)). The data revealed 119 significant performance reductions, 145 nonsignificant findings, and 6 significant improvements after SS. Unfortunately, 42 studies failed to adequately report either mean changes (16 nonsignificant and 2 significant; 7% of total findings) or pre- and poststretch means ± SD data (36 significant and 38 nonsignificant; 27% of total findings), which prevented the inclusion of ES for these measures. The weighted estimates of the remaining 178 measures revealed a moderate 3.7% mean performance reduction (Table 1). Thus, although there are some occasions in which large or very large reductions are reported (e.g., Trajano et al. 2014), SS generally induces moderate mean (<5%) performance impairments when testing is performed within minutes of stretching. Given the substantial between-study differences in poststretch changes (range, +5% to –20.5%), closer examination of the possible variables that influence the likelihood and magnitude of performance change after SS is required.

Dose–response relationship

Several original (Kay and Blazevich 2008; Knudson and Noffal 2005; Robbins and Scheuermann 2008; Siatras et al. 2008) and review (Behm and Chaouachi 2011; Kay and Blazevich 2012) articles report a clear dose–response relationship, with ≥60 s of SS being more likely to result in a significant performance impairment, but shorter durations having little effect (Behm and Chaouachi 2011; Kay and Blazevich 2012). Thus, studies were separated into those in which total stretch duration per muscle group was <60 s and those in which it was ≥60 s. Thirty-nine studies incorporating 60 maximal performance measures used <60 s of SS, with 45 nonsignificant changes reported. Statistically significant

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/apnm-2015-0235.

Table 1. Summary of data from Supplementary Table S1[1] on static stretching studies.

Characteristics	*N*	Study type	Warm-up	Stretch duration (min)	Stretch intensity	Intervention to post-test time (min)	Weighted effect and % change in performance (%)	Weighted effect size
125 studies; 270 findings	2226	RC 54	38 no warm-up	—	14 Pain; 76 POD	—	—	—
Weighted means ± SD	18.1±8.9	CC 56	69 CV or submaximal contractions	3.2±3.9	9 Sens; 26 NR	3.2±3.5	−3.4±5.9 (with 0s) −3.7±6.2 (no 0s)	0.18±0.29 (with 0s) 0.25±0.34 (no 0s)
95% CI	14.6, 21.6	15 repeated measures	18 CV and task-specific combined	2.4, 4.0	—	2.5, 3.9	−2.7, −4.1 (with 0s) −3.0, −4.5 (no 0s)	0.14, 0.21 (with 0s) 0.20, 0.30 (no 0s)

Note: "With 0s" refers to calculations in which means and effect sizes were given values of zero (0) when data for nonsignificant changes were not published, and "no 0s" refers to calculations that excluded studies that did not report data for nonsignificant changes. CC, counterbalanced control; CI, confidence interval; CV, cardiovascular; *N*, number of participants; NR, not reported; POD, point of discomfort; RC, randomized control; Sens, stretch sensation.

reductions (range, −1.2% to −8.5%) were found in 10 measures, including sprint running velocity (Fletcher and Jones 2004), jump height (Hough et al. 2009), and knee extensor MVC (Siatras et al. 2008). Interestingly, significant improvements (range, +1.6% to +4.1%) were also found in 5 measures, including sprint running time (Little and Williams 2006), jump height (Murphy et al. 2010*b*), and peak cycling power (O'Connor et al. 2006). However, because most findings were nonsignificant, it is unsurprising that the weighted estimates revealed a small 1.1% mean reduction in performance. Ninety-eight studies incorporating 210 maximal performance measures using longer stretch durations (≥60 s) revealed 109 significant reductions, 100 nonsignificant findings, and only 1 significant improvement. Given the greater prevalence of significant reductions, it was not surprising that the weighted mean change was larger (−4.6%) (Supplementary Table S4[1]). Thus, despite the clear dose–response relationship, the likely effect on performance was moderate (<5%) even after longer stretch durations, although in many contexts these impairments will be practically relevant (e.g., in elite competitions such as sprinting, long and high jumps, throws (discus, javelin, shot), and others).

Effect of SS in different performance tasks

To determine whether SS produced similar performance changes in different performance activities, the findings of the studies were separated into power–speed- or strength-based tasks. Fifty-two studies reported 82 power–speed-based measures (i.e., jumping, sprint running, throwing), with 56 nonsignificant changes, 21 significant reductions, and 5 significant improvements; collectively, there was a small 1.3% reduction in performance. Seventy-six studies reported 188 strength-based measures (i.e., 1-RM, MVC), with 79 nonsignificant changes, 108 significant reductions, and only 1 significant improvement. There was a moderate reduction in performance (−4.8%), which indicates a more substantial effect of SS on strength-based activities. The stretch durations imposed between activity types were considerably longer for strength-based activities (5.1 ± 4.6 min) than for power–speed-based activities (1.5 ± 1.6 min), which may explain the greater mean performance reductions after SS.

Dose–response effect in power–speed tasks

Twenty-six studies incorporating 38 power–speed-based measures used <60 s of SS, with 29 nonsignificant changes, 4 significant reductions, and 5 significant improvements in performance; collectively, there was a trivial change in performance (−0.15%) (Supplementary Table S4[1]). It is interesting to note that although most of the findings were not statistically significant after short-duration stretching, a greater number of significant improvements than reductions were found in jumping (Murphy et al. 2010*b*), sprint running (Little and Williams 2006), and cycling (O'Connor et al. 2006) performances. Thus, there is no clear effect of short-duration SS on power–speed-based activities, although changes may be observed on a study-by-study (and hence, subject-by-subject) basis. Nonetheless, when 28 power–speed-based studies (44 measures) using ≥60 s of stretching were examined, 27 nonsignificant changes and 17 significant reductions were found, with no study reporting a significant performance improvement. Compared with shorter-duration stretching, the mean reductions were marginally greater (−2.6%) (Supplementary Table S4[1]). Despite a greater likelihood and magnitude of effect of longer-duration SS, changes are most likely to be small to moderate.

Dose–response effect in strength tasks

Fourteen studies incorporating 22 maximal strength–based measures imposed <60 s of SS, with 16 nonsignificant changes, 6 significant reductions, and no significant improvements in performance being reported; collectively, there was a moderate reduction in performance (−2.8%) (Supplementary Table S4[1]). However, when strength-based studies using ≥60 s were examined, 72 studies incorporating 166 measures with 73 nonsignificant changes and 92 significant reductions were found; only 1 significant improvement in performance was observed. Compared with shorter-duration stretches, the mean 5.1% reduction was greater. Mean changes are clearly greater for strength- than for power–speed-based tasks regardless of duration (although this may be the result of strength-based studies using substantially longer stretch durations), and the dose–response effect remains clear.

Dose–response effect for contraction types

Similar moderate-to-large reductions were reported in studies measuring concentric (−4.4%) and eccentric (−4.2%) strength, with slightly greater mean reductions in isometric strength (−6.3%). Studies were further separated based on stretch durations (<60 s vs. ≥60 s), with a negative dose-dependent effect of stretch on concentric (<60 s, −1.5%; ≥60 s, −4.8%) and isometric (<60 s, −4.5%; ≥60 s, −6.8%) strength calculated for shorter and longer stretch durations. respectively. Only 9 studies examined the influence of SS on eccentric strength, incorporating 23 measurements and all imposing ≥60 s of stretch. Thus, dose-dependent effects cannot be examined suitably in this context. Nonetheless, 3 studies (Brandenburg 2006; Sekir et al. 2010; Costa et al. 2013) reported significant reductions in a total of 8 eccentric strength measures, whereas 6 studies (Ayala et al. 2014; Cramer et al. 2006, 2007; Gohir et al. 2012; McHugh and Nesse 2008; Winke et al. 2010) reported no change in 15 eccentric measures (≥60 s, −4.2%); these small-to-moderate changes are similar to those observed when isometric and concentric testing were completed (Supplementary Table S4[1]). Considering that most muscle strain injuries occur during the eccentric phase in most activities (Orchard et al. 1997), the limited number of studies describing the effect of SS on maximal eccentric strength is problematic, especially given that no studies have examined the effects of shorter stretch durations. The limited data available on the impact of longer-duration SS on eccentric strength suggest that a small negative effect may be likely; nonetheless, the influence of shorter durations of SS on eccentric strength remains to be studied properly.

Table 2. Summary of data from Supplementary Table S2[1] on dynamic stretching studies.

Characteristics	*N*	Study type	Stretch duration per muscle	Rest period–stretch	Intervention to post-test time (min)	Effect and % change in performance (%)	Effect size
Total 48 studies	1216	42 CC	NA	—	—	86 measures	—
Weighted means ± SD	25.3±16.9	5 repeated measures	NA	15.7±7.2 s	4.94±7.91	1.25±4.53 (with 0s) 1.35±4.71 (no 0s)	0.33±0.62 (with 0s) 0.35±0.64 (no 0s)
95% CI	20.4, 30.2	1 Single blind CC	NA	12.8 s, 18.6 s	3.0, 6.9	0.26, 2.24 (with 0s) 0.26, 2.44 (no 0s)	0.2, 0.46 (with 0s) 0.21, 0.49 (no 0s)

Note: "With 0s" refers to calculations in which means and effect sizes were given values of zero (0) when data for nonsignificant changes were not published, and "no 0s" refers to calculations that excluded studies that did not report data for nonsignificant changes. "Rest period–stretch" refers to the recovery time between repetitions. All percentage changes and effect sizes compare the dynamic stretch intervention with a control measure where possible. CC, counterbalanced control; *N*, number of participants; NA, not available.

Effect of muscle length on SS-induced performance changes

Five studies examined whether the muscle length adopted during testing influenced the subsequent strength loss (Nelson et al. 2001; Herda et al. 2008; McHugh and Nesse 2008; McHugh et al. 2013; Balle et al. 2015). Four studies examined the knee flexors (Herda et al. 2008; McHugh and Nesse 2008; McHugh et al. 2013; Balle et al. 2015) and the other examined the knee extensors (Nelson et al. 2001). All 5 studies demonstrated marked strength loss at short muscle lengths (–10.2%), which contrasted with moderate strength gains at the longest muscle lengths tested (+2.2%). Notwithstanding this, potential reductions in maximal force may be notable in activities performed at shorter muscle lengths, yet performance may be enhanced in activities performed at longer muscle lengths; this may be of practical importance given that muscle strain injuries are more likely to occur with the muscle at a longer, rather than a shorter, length.

Effect of SS in different muscle groups

Lower-limb strength was examined in 67 of the 75 studies in which strength tests were completed. Overall, similar responses were observed in the knee extensors (–3.7%), knee flexors (–6.3%), and plantar flexors (–5.6%). When these studies were further separated based on the stretch duration (<60 s vs. ≥60 s per muscle group), evidence for a dose-dependent effect of stretch was observed in the knee extensors (<60 s, –2.6%; ≥60 s, –3.8%), knee flexors (<60 s, –4.8%; ≥60 s, –6.4%), and plantar flexors (<60 s, –3.5%; ≥60 s, –5.9%). Taken together, these data are indicative of a dose-dependent effect of stretch, with similar moderate-to-large mean changes calculated for all muscle groups after shorter and longer stretch durations, respectively. However, considering the large 95% CIs in several of the findings (Supplementary Table S4[1]), some caution should be used when interpreting the mean changes reported, because substantial variability exists among studies.

Dynamic stretching

DS involves the performance of a controlled movement through the ROM of the active joint(s) (Fletcher 2010). For a number of reasons, DS is sometimes considered preferable to SS in the preparation for physical activity. First, there may be a close similarity between the stretching and exercise movement patterns (Behm and Sale 1993). Second, DS activities can elevate core temperature (Fletcher and Jones 2004), which can increase nerve conduction velocity, muscle compliance, and enzymatic cycling, accelerating energy production (Bishop 2003). Third, DS and dynamic activities tend to increase rather than decrease central drive, as may occur with prolonged SS (Guissard and Duchateau 2006; Trajano et al. 2013).

An examination of the data (48 studies incorporating 80 measures) (Table 2, Supplementary Table S2[1] and Supplementary Fig. S1*b*[1]) revealed that the weighted mean performance enhancement associated with DS was 1.3%. Unsurprisingly, given the modest changes, almost one-half of the measurements (37 of 80) demonstrated trivial magnitude changes, with only 6 studies reporting subsequent small-to-large relative performance impairments (Nelson and Kokkonen 2001; Bacurau et al. 2009; Curry et al. 2009; Barroso et al. 2012; Franco et al. 2012; Costa et al. 2014). Thus, although there are occasions in which moderate or large improvements in performance are reported, overall, no robust evidence exists for substantial performance enhancements after DS.

Dose–response relationship for DS

Most studies did not report specific stretch durations but rather, gave descriptions of the number of exercises, sets, and repetitions. The weighted mean DS workload was 49.2 repetitions (95% CI 25.1–73.2). When reported, 11 studies had set durations of 30 s, 8 studies used 15-s set durations, and 4 studies used set durations of 20, 25, and 40 s, respectively (Table 2 and Supplementary Table S2[1]). Behm and Chaouachi (2011) reported a DS dose–response effect in which greater overall peak force and power improvements were observed when >90 s (7.3% ± 5.3%) vs. <90 s (0.5% ± 2.3%) of DS was imposed immediately before testing. However, trivial ES or statistically nonsignificant performance changes were also elicited by both longer DS durations of 10 min (Needham et al. 2009) and 15 min (Zourdos et al. 2012) and by 180 repetitions (Herda et al. 2008), as well as by shorter durations, such as 45 s (Beedle et al. 2008), 60 s (Samuel et al. 2008), and 150 s (Amiri-Khorasani et al. 2010), or 2 repetitions of 4 exercises (Dalrymple et al. 2010). Hence, based on the variability among studies, it is difficult to demonstrate a dose–response relationship with DS.

Effect of DS on strength vs. power measures

Force measurements have been performed using isometric or slower, dynamic movements (e.g., leg extensions, squats); thus, the test movement velocity does not always correspond with the DS movement velocity. The data analysis revealed small weighted changes for both strength-based performances (18 measures) and power-based tests (51 measures) (Table 2). When evaluated further, moderate mean improvements of 2.1% were observed for jump performances (34 measures), whereas repetitive actions such as running or sprinting or agility (17 measures) showed a small 1.4% improvement. The lack of movement velocity similarity between the leg press and DS activities may have been a factor, with a trivial (4 measures) mean impairment of –0.23%. This may indicate that part of the positive effect of DS comes from allowing practice at tasks similar to those in the tests.

Effect of DS by contraction type

Only 11 studies tested specifically during concentric (16 measures) or eccentric (3 measures) contractions (Table 2 and Supplementary Table S4[1]). There was a trivial average 0.4% increase in concentric force or torque (Supplementary Table S4[1]). The 3 eccentric measures meeting our criteria had extensive variability (Supplementary Table S4[1]), and thus, the relatively small percentage decrease (–1.2%) is not truly reflective. Hence, the limited data indicate generally inconsequential contraction type–dependent effects of DS on force production.

Effect of DS movement frequency

The stretch frequency and ROM (and possibly perceived intensity) of stretches may also influence the effect of DS. Some studies do not report stretch intensity (Manoel et al. 2008; Dalrymple et al. 2010), but some report movement frequency (i.e., the number of dynamic movements per unit time) (Bacurau et al. 2009; Fletcher 2010). Higher frequencies of DS and ballistic stretching (stretching using momentum in an attempt to exceed the normal ROM, which can include bouncing) may augment spindle reflex afferent excitation of the motor neurons and may theoretically affect subsequent performance (Matthews 1981). Fletcher (2010) reported that dynamic leg swings at 100·min^{-1} resulted in significantly greater (6.7%–9.1%) countermovement jump and drop jump heights than did DS activities at 50·min^{-1}. However, even the lower-frequency DS (50·min^{-1}) elicited 3.6% significantly greater jump performances than did a no-stretch condition. Studies combining both slow and faster rates of dynamic movements in the same preactivity routine have reported significant improvements in vertical jump height (4.9%) (Hough et al. 2009), hamstrings and quadriceps eccentric and concentric torque (~7%–15%) (Sekir et al. 2010), and leg extension power (10.1%) (Yamaguchi et al. 2007). However, Franco and colleagues (2012) combined slow and fast movements (3 exercises, with 5 slow plus 5 fast movements) and reported a decrease in Wingate peak power and time to peak power (mean and % changes were not provided). Cycling is not a DS-shortening cycle movement, so this negative result is consistent with the previously discussed potential for a movement pattern–specific effect of DS.

Inconsistent results are reported with the use of ballistic or bobbing (bounce through the movement at the end of ROM) movements. Both Bacurau and colleagues (2009) and Nelson and Kokkonen (2001) used 20 min of ballistic stretch activities and reported a 2.2% decrease in leg press 1-RM and a ~5%–7% decrease in knee flexion and extension 1-RMs, respectively (likely fatigue related). Other studies imposing shorter durations of ballistic stretching or bobbing actions at end ROM have reported no significant effects (Bradley et al. 2007; Samuel et al. 2008). Cumulatively, the data show a tendency toward an increase in performance with faster and/or more intense ballistic stretches, but substantial variability exists among studies and with regard to performances in different tests within studies, so a firm conclusion cannot be drawn.

Effect of magnitude of DS movement on performance

The ROMs adopted during DS vary considerably among studies, with authors describing "ROM" as a DS through the active ROM, maximal or end of ROM, exaggerated movements, bobbing, bouncing, ballistic bouncing movements (indeterminate ROM extent), mild stretch, and others. Most studies report that movements were performed through a full or nearly full active ROM. Stretches performed through the active or maximal ROM resulted in trivial and nonsignificant performance changes (Beedle et al. 2008; Herda et al. 2008; Curry et al. 2009; Amiri-Khorasani et al. 2010; Chaouachi et al. 2010; Paradisis et al. 2014), performance enhancements (Fletcher and Anness 2007; Yamaguchi et al. 2007; Chaouachi et al. 2010), or performance impairments (Curry et al. 2009). Two studies reporting performance impairments required subjects to perform small ballistic bouncing or bobbing movements near the end ROM (Nelson and Kokkonen 2001; Bacurau et al. 2009). Studies using "exaggerated movements", which may or may not reach the end of the active ROM, report both performance impairments (Costa et al. 2014) and no significant effect (Dalrymple et al. 2010). Thus, there is no identifiable trend as to the effects associated with DS through a full (maximal) or nearly full (submaximal) ROM.

PNF stretching

PNF stretching incorporates SS and isometric contractions in a cyclical pattern to enhance joint ROM, with 2 common techniques being contract relax (CR) and contract relax agonist contract (CRAC) (Sharman et al. 2006). The CR method includes an SS phase followed immediately by an intense, isometric contraction of the stretched muscle, with a further additional stretch of the target muscle completed immediately after contraction cessation. On the other hand, the CRAC method requires an additional contraction of the agonist muscle (i.e., opposing the muscle group being stretched) during the stretch, prior to the additional stretching of the target muscle (Sharman et al. 2006). Despite its efficacy in increasing ROM, PNF stretching is rarely used in athletic preactivity routines, possibly because (*i*) there is normally a requirement for partner assistance, (*ii*) it may be uncomfortable or painful, and (*iii*) muscle contractions performed at highly stretched muscle lengths can result in greater cytoskeletal muscle damage (Butterfield and Herzog 2006) and speculatively an increased risk of muscle strain injury (Beaulieu 1981), although no data clearly support this. Notwithstanding these potential limitations, PNF stretching remains an effective practice and its impact on muscular performance is worthy of examination.

Relatively few studies report the effects of PNF stretching, and no comprehensive or meta-analytical review exists that evaluates the effects of PNF stretching. This is surprising because PNF is a highly effective stretching method for ROM gain and includes an SS phase within the protocol and thus may be predicted to influence physical performance. Our search revealed 14 studies reporting the effects of PNF stretching on performance, with 11 using the CR method and 3 using CRAC. Because of the limited number of studies using CRAC, and the differences in methodology across stretching modes, we have reported only on CR stretching. Eleven studies incorporated 23 performance measures (Table 3, Supplementary Table S3[1], and Supplementary Fig. S1*c*[1]) examining the acute effects of CR PNF stretching on maximal muscular strength and power performance. Seventeen nonsignificant findings and 6 significant performance reductions were reported; no studies reported a performance improvement immediately after PNF stretching. Although the majority of studies reported no significant change in performance, our weighted estimate showed a 4.4% mean reduction in performance (Table 3). Thus, although notable performance impairments have been reported, PNF stretching generally induces small-to-moderate changes in performance that may be meaningful only in some clinical or athletic environments.

Dose–response relationship

The limited number of studies imposing PNF stretching, coupled with the relatively small range of stretch durations (5–50 s), made an examination of the dose–response relationship impossible. The CR routine was normally repeated 2–5 times, providing an average SS phase of 2.5 ± 2.9 min. Based on our report of the effects of SS using durations >60 s, it may be concluded that the deficit induced by SS (–4.6%) is similar to that induced by PNF stretching (–4.4%). However, 9 of the 11 studies incorporating PNF stretching also compared the results with an SS condition, which enabled a direct comparison of the 2 stretch modes and eliminated stretch duration as a confounding factor. These studies showed that SS had a smaller negative impact (–2.3%) than did PNF stretching (–6.4%), indicating a more substantive effect after PNF. Regardless, the data are indicative of a small-to-large effect of PNF stretching on maximal muscular performance.

Effect of PNF on power–speed tasks

Three studies reported 4 vertical jump performances, including squat and countermovement jump heights. One study reported a moderate-to-large and statistically significant reduction (–5.1%) in jump height (Bradley et al. 2007); however, this effect was no

Table 3. Summary of data from Supplementary Table S3[1] on proprioceptive neuromuscular facilitation stretching studies.

Characteristics	*N*	Study type	Warm-up	Contraction intensity	Stretch intensity	Intervention to post-test time (min)	Weighted reduction in performance (%)	Weighted effect size
Total 11 studies	229	9 RC	2 no warm-up, 8 CV or submaximal contractions, 1 CV and task-specific combined	6 maximal, 4 submaximal, 1 NR	2 Pain, 6 POD, 1 Sens, 2 NR	—	23 measures	—
Weighted means ± SD	20.8±17.0	2 CC	—	—	—	4.1±4.7	−3.8±6.3 (with 0s) −4.4±6.4 (no 0s)	0.07±0.15 (with 0s) 0.12±0.20 (no 0s)
95% CI	5.2, 36.5	—	—	—	—	0.00, 8.3	−1.2, −6.4 (with 0s) −1.5, −7.3 (no 0s)	0.01, 0.14 (with 0s) 0.02, 0.22 (no 0s)

Note: CC, counterbalanced control; CV, cardiovascular; *N*, number of participants; NR, not reported; POD, point of discomfort; RC, randomized control; Sens, stretch sensation.

longer observed at 15 min after stretch; no significant difference was reported in the remaining 2 studies (Christensen and Nordstrom 2008; Young and Elliott 2001). One study (Bradley et al. 2007) examining 2 jump measures did not report either the mean changes or pre- and poststretch results, which prevented the calculation of ES for these measures. Nonetheless, analysis of the available data revealed a small mean reduction (−1.6%); thus, any impact on jump performance is likely to be trivial to small (Supplementary Table S4[1]).

Effect of PNF on strength tasks

Eight PNF studies examined 19 strength-based measures; 16 nonsignificant findings and only 3 significant losses were reported. One study (Reis et al. 2013) did not report percentage changes, which would have enabled weighted estimate calculation, whereas another study (Balle et al. 2015) did not report pre- and poststretching results, which would have enabled ES calculation. Nonetheless, the weighted estimate for the available findings revealed a large mean performance reduction (−5.5%); however, large 95% CIs (Supplementary Table S4[1]) indicate a highly variable impact on muscular strength that may be practically meaningful yet small in comparison to interindividual variability in strength scores.

Effect of PNF on different contraction types

Five studies reported 11 findings pertaining to concentric strength with a moderate mean reduction (−2.1%) observed. Four studies reported 8 findings pertaining to isometric strength with a larger but variable effect (−8.3%) (Supplementary Table S4[1]). However, 1 study (Reis et al. 2013) did not report percentage change data for its nonsignificant finding, whereas another study (Balle et al. 2015) did not report pre- and poststretching results, which would have enabled ES calculation. Thus, caution should be used when interpreting our estimate given the proportionally large number of studies omitted from the analysis. Interestingly, no studies were found that examined the influence of PNF stretching on eccentric strength. Considering that eccentric strength (Orchard et al. 1997) is a factor purported to influence muscle strain injury risk, and that most muscle strain injuries occur during the eccentric phase of activities, the influence of PNF stretching on eccentric strength requires further investigation.

Stretching-induced force loss mechanisms

Understanding the mechanisms underpinning the stretch-induced force loss allows us to make sense of between-study differences in results and to develop strategies to overcome any force and/or performance reductions. Minimal evidence has been presented as to how DS affects the neuromuscular system, although one may speculate that its effects are similar to those of other dynamic warm-up methods (e.g., Bishop 2003); thus, this section focuses on the effects of SS and PNF stretching.

Changes in tendon stiffness and the force–length relationship

Acute muscle stretching has been hypothesized as reducing tendon stiffness, forcing the muscle to work at shorter and weaker (according to its force–length relationship) lengths (Cramer et al. 2007; Fowles et al. 2000; Nelson et al. 2001; Weir et al. 2005). Indeed, several studies have demonstrated greater stretch-induced strength loss at short vs. long muscle lengths (e.g., Nelson et al. 2001; Herda et al. 2008), although this effect may also be explained by muscle length–specific reductions in central (neural) drive (see Reduced central (efferent) drive). Evidence against this hypothesis includes data showing that gastrocnemius works at the same length after acute muscle stretching despite a reduction in peak force production (Kay and Blazevich 2009); thus, muscle length did not cause the force decline. In addition, potential reductions in muscle length would not affect, or may even increase, force production in muscles working at optimum length or on the descending limb of their force–length relation. Given our current understanding, changes in muscle length are unlikely to be an important mechanism influencing the force reduction after SS.

Stretch-induced contractile "fatigue" or damage

Mechanical stretch imposed on the muscle–tendon unit could cause damage within the muscle itself, thus reducing contractile force capacity (i.e., length at optimum force) (Brooks et al. 1995). Decreases in electrically stimulated force after acute plantar flexor stretches (Trajano et al. 2013, 2014) may be considered evidence for the hypothesis; however, these reductions were disproportionally smaller than, and not correlated with, the loss of voluntary force and were not correlated with the recovery of force after stretch (Trajano et al. 2014). As yet, practically meaningful muscle damage has not been reported after SS in humans.

Muscle stretching may also reduce blood flow and tissue oxygen availability, causing an accumulation of metabolic end products and/or reactive oxygen and nitrogen species (Palomero et al. 2012). In animal studies, passive stretching has increased nitric oxide (Tidball et al. 1998) and reactive oxygen species (Palomero et al. 2012) production. No direct measurements have been made in humans; however, Trajano and colleagues (2014) observed that intermittent stretching (15 s rest between 5 stretches of 1 min each) caused notable perfusion and reperfusion of plantar flexor muscles and a greater magnitude of and longer-lasting force loss than did the same volume of continuous stretching, even though the absolute level of deoxygenation was greater during continuous stretches. Thus, ischemia–reperfusion cycles induced by intermittent stretching appear to be particularly problematic. The mechanism by which these cycles impair force production is not known specifically, but it appears not to be caused by a decrease in intracellular free calcium concentration (Trajano et al. 2014).

Diminished electromechanical coupling

Theoretically, impaired sarcolemmal action potential transmission may impair calcium release during muscle activation. Eguchi and colleagues (2014) observed decreases in electromyography (EMG) signal frequency during 30-s low-intensity (submaximal) deltoid contractions after 30-s SS or DS; however, it is not clear whether this indicates a change in sarcolemmal transmission or a shift in the motor unit recruitment pattern towards lower-threshold (e.g., type I) motor units. Furthermore, Trajano and colleagues (2014) reported no change in M-wave amplitude after 5 plantar flexor stretches of 1 min each. No other studies have made such measurements, and no studies have used other methods such as assessment of action potential velocity or EMG frequency characteristics during maximal, or maximally fatiguing, contractions.

Changes in tendon stiffness also speculatively influence electromechanical delay (Cresswell et al. 1995; Waugh et al. 2013, 2014) and thus reduce the rate of force production. However, despite correlations being observed between tendon stiffness (or changes with exercise training) and electromechanical delay (or its change with training) (Waugh et al. 2013, 2014), this effect has not been shown explicitly. Reductions in tendon stiffness are also thought to affect the rate of force development (Bojsen-Møller et al. 2005; Waugh et al. 2013). However, small changes in tendon stiffness (e.g., a 30% increase after strength training in children) do not appear to influence the rate of force development (Waugh et al. 2014) so it is unlikely that the changes in tendon stiffness elicited by acute muscle stretching meaningfully influence it.

In addition, muscle stretching theoretically could reduce the force transfer efficiency from the contractile component to the skeleton (e.g., endo-, epi-, and perimysial transmission) (Huijing 1999) alongside the stretch-induced reductions in muscle stiffness (Kay and Blazevich 2009; Morse et al. 2008). However, this possibility has not been assessed directly in humans.

Reduced central (efferent) drive

Associations between reductions in EMG amplitude and maximal voluntary force production have been observed (Fowles et al. 2000; Kay and Blazevich 2009). However, others report no changes in EMG amplitude (e.g., Herda et al. 2008; Ryan et al. 2008), so a consensus cannot be reached regarding changes in central drive as assessed using EMG. Nonetheless, reductions in the EMG/M ratio (reducing peripheral influences on EMG amplitude), voluntary activation levels (measured using the interpolated twitch technique), and V-wave amplitude (a variant of the H reflex providing evidence of voluntary drive to the motoneurons) have been observed after stretch (Trajano et al. 2013, 2014). Furthermore, these variables increased in the early period (<15 min) after stretch, and their changes were correlated with the changes in maximal force production (e.g., Trajano et al. 2013, 2014). Indeed, the simultaneous recoveries of voluntary force and central drive (EMG) have been observed in other studies. Thus, changes in central drive appear to underpin changes in muscular force production after stretching.

Central drive can be modulated by sensory (afferent) inputs (Matthews 1981), which may modulate supraspinal outflow from the motor cortex. Alternatively, reductions in muscle spindle–dependent feedback to the motoneuron pool (i.e., at the spinal cord), reductions in intrafusal (muscle spindle) discharge leading to a reduction in voluntary drive onto the motoneurons via the γ-loop, altered excitability of spinal interneurons (facilitatory and inhibitory), or a change in excitability of the postsynaptic membrane may contribute. Recent evidence suggests that muscle stretching can reduce persistent inward current formation at the motoneurons (Trajano et al. 2014), which probably occurs via a reduced muscle spindle facilitation of the motoneuron. Thus, changes at the spinal level appear to be closely linked with the reduction in muscle force. Given that inward currents are amplified by central nervous system stimulants (e.g., caffeine), emotional arousal, and the simultaneous contraction of other muscles, such findings hint at potential interventions that may reduce the loss of force after muscle stretching. Persistent inward current formation was also greater at longer than at shorter muscle lengths, which may partly explain the greater loss of muscle force at shorter muscle lengths (Herda et al. 2008; McHugh et al. 2013).

Acute effects of SS, DS, and PNF on joint ROM

Although SS, DS, and PNF can significantly increase passive ROM (Sharman et al. 2006), whether PNF, SS, or DS provide greater acute ROM benefits is disputed. A number of studies report greater ROM improvements after PNF compared with SS within a single session (Etnyre and Lee 1988; Ferber et al. 2002; O'Hora et al. 2011). On the other hand, SS has also been shown to provide ROM increases similar to those of PNF within a single session (Condon and Hutton 1987; Maddigan et al. 2012). There is also conflict in the DS literature, with some studies reporting that an acute bout of DS provides either similar (Beedle and Mann 2007; Perrier et al. 2011) or greater (Duncan and Woodfield 2006; Amiri-Khorasani et al. 2011) increases in flexibility than does SS, whereas many other studies have reported that DS was not as effective as SS within a single preactivity routine (Samuel et al. 2008; Bacurau et al. 2009; Sekir et al. 2010; Barroso et al. 2012; Paradisis et al. 2014). Few studies have compared PNF with DS; however, Wallin and colleagues (1985) showed greater ROM increases after PNF (11%–24%) than after ballistic stretching (3%–7%) over 14 training sessions. Small-to-large relative ROM increases have been reported to persist for 5 (Whatman et al. 2006), 10 (Behm et al. 2011), 30 (Fowles et al. 2000), 90 (Knudson 1999), and 120 min (Power et al. 2004) after SS. Unfortunately, ROM changes after DS and PNF have been monitored only for a maximum of 10 min after stretch. Although it is not possible to confidently rank stretching methods on their effectiveness in increasing flexibility, all 3 forms of stretching have been shown to increase ROM.

ROM mechanisms after acute muscle stretching

SS, DS, and PNF stretching have distinct loading characteristics that likely influence the specific mechanisms responsible for acute increases in ROM. However, our understanding of the underlying mechanisms remains limited. Acute increases after SS have been attributed largely to concomitant increases in the capacity to tolerate loading prior to stretch termination (i.e., stretch tolerance) (Magnusson et al. 1996*a*) and/or to changes in mechanical properties (i.e., reduced muscle stiffness) (Morse et al. 2008). However, although both mechanisms are reported commonly, substantial differences in study methodology (duration, intensity, muscle group, subject demographics) limit our ability to fully determine the importance of these mechanisms to increases in ROM after SS.

Historically, autogenic inhibition has been theorized to explain PNF's superior efficacy to enhance ROM (Hindle et al. 2012), because the intense isometric contraction phase was thought to increase Ib muscle afferent activity. This activity may hyperpolarize the dendritic ends of spinal α-motoneurons of the stretched muscle, minimizing or removing the influence of stretch-induced type Ia–mediated reflexive activity (McNair et al. 2001), enabling further increases in ROM. However, there is no direct evidence of a causal relationship between reflexive activity and ROM, and several studies report increased resting EMG activity immediately after the contraction phase of a PNF stretch (Magnusson et al. 1996*a*; Mitchell et al. 2009). Consequently, debate exists as to the involvement of autogenic inhibition (Hindle et al. 2012; Sharman et al. 2006). However, because PNF stretching includes an SS phase, SS and PNF likely share common mechanisms underpinning acute increases in ROM. In fact, increased stretch tolerance (Mitchell et al. 2007) and reduced stiffness (Magnusson et al. 1996*b*) have both been reported after PNF stretching. However, distinct tissue property changes are reported after PNF, with reductions in tendon stiffness also reported (Kay et al. 2015), although changes in stiffness were not correlated with changes in ROM. Thus, it is likely that similar underlying mechanisms are associated with changes in ROM after PNF and SS modalities.

DS involves repeated cyclical loading and unloading of the musculature, often for several minutes (Fletcher 2010). Despite the ability of DS to increase ROM, there have been limited attempts to identify the influential mechanisms, and no clear mechanism(s) have been identified. However, repetitive lengthening of the musculature can increase muscle fibre temperature, decrease viscosity, and increase extensibility in animal models (Mutungi and Ranatunga 1998), with 1 study reporting reductions in passive muscle stiffness with increased ROM after DS in humans (Herda et al. 2013). Thus, limited data exist describing the mechanisms for ROM enhancement after DS, and it is not known whether changes in stretch tolerance are as influential as in SS and PNF forms of stretching.

Influence of preactivity stretching on injury risk

Effect of preactivity stretching on subsequent injury risk

Stretching is generally incorporated into the preactivity routine in numerous sports. For the purposes of this review, studies reporting the effects of stretching that were performed only after exercise, or as part of a holistic training program not specifically before exercise, were not included. All 12 studies used some type of SS or PNF stretching, with none using DS (Supplementary Tables S5*a* and S5*b*[1]).

Eight studies showed some effectiveness of stretching, whereas 4 showed no effect. Of practical importance, there was no evidence that stretching negatively influences injury risk. Several of the studies had design limitations that made it difficult to confidently attribute an apparent injury reduction effect specifically to the preactivity muscle stretching.

The 12 studies were assessed with respect to 5 potentially confounding factors summarized below.

Study design (randomized trials vs. other study designs)

Although a lower proportion of randomized (4 of 7) than nonrandomized (4 of 5) trials showed a benefit of stretching with respect to injury reduction (mostly muscle injuries), it is notable that the majority of randomized trials showed some efficacy.

Stretch duration (short vs. long stretch durations)

Five studies imposed stretching interventions lasting ≤5 min. Of these, 2 showed a benefit of stretching, 1 of which was a survey-driven retrospective correlation analysis, indicating that hamstring injury rates were lower in teams reporting the use of stretching (Dadebo et al. 2004). Six studies imposed total stretch durations >5 min, with 5 showing some benefit of stretching with respect to injury risk. One study did not report stretch duration. Thus, longer (total)-duration stretching interventions may have a greater potential to decrease injury risk.

Three studies imposed stretches on single muscle groups (2 on hamstrings, 1 on plantar flexors). The other 9 studies imposed stretches on multiple muscle groups. For example, Pope and colleagues (2000) imposed single 20-s stretches on bilateral gastrocnemius, soleus, hamstrings, quadriceps, hip adductors, and hip flexors. Thus, the total stretch time for single muscle group studies is not directly comparable with that of multiple muscle group studies. However, some stretches targeting a single muscle group (e.g., straight leg raise hamstring stretch) may also stretch ipsilateral (e.g., calf) and contralateral (e.g., hip flexors) muscle groups.

Type of sport–activity (endurance activities with a predominance of overuse injuries vs. sprinting sports with a high prevalence of muscle injuries)

Five studies examined injury rates in endurance sports or military training in which there was a predominance of overuse injuries. Only 2 of the studies showed a benefit of stretching, with reduced muscle injuries being the common finding. Six studies involved sprint running–type sports, with fewer muscle injuries reported in 5 of the 6 studies with stretching (1 addressed ankle sprains only). The 1 longitudinal study (Hadala and Barrios 2009), completed on yachting crews, was not included in this comparison because it did not fit either activity classification (it showed a benefit of stretching on muscle injuries). Overall, the current research indicates that preactivity stretching may be beneficial for injury prevention in sports with a sprint running component but not in endurance-based running activities (including military training) with a predominance of overuse injuries.

Stretching with vs. without warm-up

Based on the current body of research, it is not possible to comment on the role of stretching with respect to injury prevention when performed with vs. without warm-up. However, because muscle stretching and warm-up may have similar effects on muscle viscoelastic properties (Taylor et al. 1997), it is possible that both may influence injury risk, and this would not be noticeable without a nonstretching, non-warm-up control group.

All-cause injury rate vs. specific injury rates

Eight studies examined all types of injuries or all lower-extremity injuries. The other 4 studies examined specific injuries, (2 studied hamstring strains, 1 studied all lower-extremity muscle strains, 1 studied ankle sprains). Of the 8 studies examining the effect of stretching on total injury rates, only 2 reported a benefit of stretching (Ekstrand et al. 1983; Hadala and Barrios 2009).

One study reported a benefit of stretching for ankle sprains (McKay et al. 2001); however, this was a retrospective survey study, and 4 randomized controlled trials have shown no benefits of stretching on the rates of ankle sprains (Amako et al. 2003; Pope et al. 1998, 2000; van Mechelen et al. 1993).

Six studies specified the effects of stretching on the prevalence of acute muscle injuries. From these studies, it was possible to compute the relative risk of sustaining an acute muscle injury associated with stretching vs. not stretching (Supplementary Table S6[1]). Taken together, these studies indicate a 54% risk reduction in acute muscle injuries associated with stretching.

One study also indicated that stretching was associated with a reduction in "bothersome soreness" (Jamtvedt et al. 2010). However, most research has demonstrated that stretching prior to exercise is ineffective in reducing soreness or other symptoms of muscle damage (Black and Stevens 2001; Gulick et al. 1996; High et al. 1989; Johansson et al. 1999; Khamwong et al. 2011; Lund et al. 1998; McHugh and Nesse 2008), with 1 recent exception showing some benefit of stretching (Chen et al. 2014).

Limitations

A number of limitations were encountered when reviewing this literature. They included issues related to internal validity (i.e., bias caused by expectancy effects) and external validity (i.e., ecological validity of stretch durations and warm-up components, description detail of stretches, reporting bias against nonsignificant results). A detailed discussion is provided as a digital supplement (Supplementary Appendix S7[1]).

Conclusions

SS- (−3.7%), DS- (+1.3%), and PNF- (−4.4%) induced performance changes were typically small to moderate in (relative) magnitude when testing was performed soon after the stretching. An initial assumption based on the overall results may be to not recommend SS or PNF stretching within pre-event warm-up activities when test performance is required immediately after stretching. However, the average poststretching measurement time was 3–5 min, which does not coincide with typical stretching-to-performance durations of >10 min in many circumstances (e.g., sports competitions). In studies that conducted tests >10 min after stretching, performance changes were typically statistically trivial unless extreme stretch protocols were used (Fowles et al. 2000; Power et al. 2004).

SS impairments were more substantial with ≥60 s (–4.6%) vs. <60 s (–1.1%) of stretching for each muscle group. Dose–response relationships could not be established firmly for PNF or DS. There is some evidence that >2 min and faster frequencies of DS provide a greater performance increase. Thus, longer-duration SS and PNF may be done well before (e.g., >10 min) task performance is required to allow effects to resolve, but DS may be performed closer to the performance. There were no significant response differences when stretching was based on muscle contraction type or muscle group stretched. Because muscle strain injuries are more likely to occur with the muscle at a longer length, the very large performance reductions (–10.2%) at short muscle lengths, but moderate performance increases (2.2%) at longer muscle lengths, could influence the decision to use SS. Although no significant differences were observed between testing types for DS and PNF, there were greater SS-induced deficits in strength (–4.8%) vs. power–speed (–1.3%) tests. There was some evidence of a movement pattern–specific effect of DS, because jump performance (2.1%) improved to a greater extent than tests involving slower, uniarticular concentric (0.4%) or eccentric (–1.2%) contractions.

The few studies that included poststretching dynamic activity (i.e., Murphy et al. 2010*a*; Samson et al. 2012) did not show substantial evidence for an effect on performance. There is no evidence as to whether there are any psychological or group–team cohesion influences on muscle stretching. All forms of muscle stretching have been shown to provide a significant acute ROM benefit. Despite some evidence for a greater ROM benefit with PNF, a confident conclusion cannot be reached based on the available evidence.

SS and PNF show no overall effect on all-cause injury or overuse injuries, but there may be a benefit in reducing acute muscle injuries with running, sprinting, or other repetitive contractions. Limited data indicate a potentially greater effect of SS and PNF on injury risk for longer stretch durations (>5 min of total stretch time of task-related multiple muscle groups). There is conflicting evidence as to whether stretching in any form before exercise can reduce exercise-induced muscle soreness. Hence, stretching in some form appears to be of greater benefit than cost (in terms of performance, ROM, and injury) but the type of stretching chosen, and the make-up of the stretch routine, will depend on the context within which it is used.

The Canadian Society for Exercise Physiology position stand recommendations based on this stretch literature review are available as a digital supplement (Supplementary Appendix S8[1]).

Conflict of interest statement

The authors declare that there are no conflicts of interest.

References

Amako, M., Oda, T., Masuoka, K., Yokoi, H., and Campisi, P. 2003. Effect of static stretching on prevention of injuries for military recruits. Mil. Med. **168**(6): 442–446. PMID:12834132.

Amiri-Khorasani, M., Sahebozamani, M., Tabrizi, K.G., and Yusof, A.B. 2010. Acute effect of different stretching methods on Illinois agility test in soccer players. J. Strength Cond. Res. **24**(10): 2698–2704. doi:10.1519/JSC.0b013e3181bf049c. PMID:20168255.

Amiri-Khorasani, M., Abu Osman, N.A., and Yusof, A. 2011. Acute effect of static and dynamic stretching on hip dynamic range of motion during instep kicking in professional soccer players. J. Strength Cond. Res. **25**: 1647–1652. doi:10.1519/JSC.0b013e3181db9f41. PMID:21358428.

Ayala, F., De Ste Croix, M., Sainz de Baranda, P., and Santonja, F. 2014. Acute effects of static and dynamic stretching on hamstrings' response times. J. Sports Sci. **32**(9): 817–825. doi:10.1080/02640414.2013.861606. PMID:24405028.

Bacurau, R.F., Monteiro, G.A., Ugrinowitsch, C., Tricoli, V., Cabral, L.F., and Aoki, M.S. 2009. Acute effect of a ballistic and a static stretching exercise bout on flexibility and maximal strength. J. Strength Cond. Res. **23**: 304–308. doi:10.1519/JSC.0b013e3181874d55. PMID:19057408.

Balle, S.S., Magnusson, S.P., and McHugh, M.P. 2015. Effects of contract-relax versus static stretching on stretch-induced strength loss and length-tension relationship. Scand. J. Med. Sci. Sports. 2015 Jan 26. doi:10.1111/sms.12399. [Epub ahead of print.].

Barroso, R., Tricoli, V., Santos Gil, S.D., Ugrinowitsch, C., and Roschel, H. 2012. Maximal strength, number of repetitions, and total volume are differently affected by static-, ballistic-, and proprioceptive neuromuscular facilitation stretching. J. Strength Cond. Res. **26**: 2432–2437. doi:10.1519/JSC.0b013e31823f2b4d. PMID:22914099.

Beaulieu, J.E. 1981. Developing a stretching program. Phys. Sports Med. **9**: 59–69.

Beedle, B.B., and Mann, C.L. 2007. A comparison of two warm-ups on joint range of motion. J. Strength Cond. Res. **21**: 776–779. doi:10.1519/00124278-200708000-00020. PMID:17685684.

Beedle, B., Rytter, S.J., Healy, R.C., and Ward, T.R. 2008. Pretesting static and dynamic stretching does not affect maximal strength. J. Strength Cond. Res. **22**: 1838–1843. doi:10.1519/JSC.0b013e3181821bc9. PMID:18841081.

Behm, D.G., and Chaouachi, A. 2011. A review of the acute effects of static and dynamic stretching on performance. Eur. J. Appl. Physiol. **111**: 2633–2651. doi:10.1007/s00421-011-1879-2. PMID:21373870.

Behm, D.G., and Sale, D.G. 1993. Velocity specificity of resistance training. Sports Med. **15**: 374–388. doi:10.2165/00007256-199315060-00003. PMID:8341872.

Behm, D.G., Bambury, A., Cahill, F., and Power, K. 2004. Effect of acute static stretching on force, balance, reaction time, and movement time. Med. Sci. Sports. **36**: 1397–1402. PMID:15292749.

Behm, D.G., Plewe, S., Grage, P., Rabbani, A., Beigi, H.T., Byrne, J.M., and Button, D.C. 2011. Relative static stretch-induced impairments and dynamic stretch-induced enhancements are similar in young and middle-aged men. Appl. Physiol. Nutr. Metab. **36**(6): 790–797. doi:10.1139/h11-107. PMID:22014144.

Bishop, D. 2003. Warm up II: Performance changes following active warm up and how to structure the warm up. Sports Med. **33**: 483–498. doi:10.2165/00007256-200333070-00002. PMID:12762825.

Black, J.D.J., and Stevens, E.D. 2001. Passive stretching does not protect against acute contraction-induced injury in mouse EDL muscle. J. Muscle Res. Cell Motil. **22**(4): 301–310. doi:10.1023/A:1013188001776. PMID:11808770.

Bojsen-Møller, J., Magnusson, S.P., Rasmussen, L.R., Kjaer, M., and Aagaard, P. 2005. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. J. Appl. Physiol. (1985). **99**(3): 986–994. PMID:15860680.

Bradley, P.S., Olsen, P.D., and Portas, M.D. 2007. The effect of static, ballistic, and proprioceptive neuromuscular facilitation stretching on vertical jump performance 176. J. Strength Cond. Res. **21**: 223–226. doi:10.1519/00124278-200702000-00040. PMID:17313299.

Brandenburg, J.P. 2006. Duration of stretch does not influence the degree of force loss following static stretching. J. Sports Med. Phys. Fit. **46**: 526–534. PMID:17119516.

Brooks, S.V., Zerba, E., and Faulkner, J.A. 1995. Injury to muscle fibres after single stretches of passive and maximally stimulated muscles in mice. J. Physiol. **488**(2): 459–469. doi:10.1113/jphysiol.1995.sp020980. PMID:8568684.

Butterfield, T.A., and Herzog, W. 2006. Effect of altering starting length and activation timing of muscle on fiber strain and muscle damage. J. Appl. Physiol. **100**: 1489–1498. doi:10.1152/japplphysiol.00524.2005. PMID:16397062.

Chaouachi, A., Castagna, C., Chtara, M., Brughelli, M., Turki, O., Galy, O., et al. 2010. Effect of warm-ups involving static or dynamic stretching on agility, sprinting, and jumping performance in trained individuals. J. Strength. Cond. Res. **24**: 2001–2011. doi:10.1519/JSC.0b013e3181aeb181. PMID:19855310.

Chen, H.M., Wang, H.H., Chen, C.H., and Hu, H.M. 2014. Effectiveness of a stretching exercise program on low back pain and exercise self-efficacy among nurses in Taiwan: a randomized clinical trial. Pain Manage. Nurs. **15**(1): 283–291. doi:10.1016/j.pmn.2012.10.003. PMID:23266331.

Christensen, B.K., and Nordstrom, B.J. 2008. The effects of proprioceptive neuromuscular facilitation and dynamic stretching techniques on vertical jump performance. J. Strength Cond. Res. **22**: 1826–1831. doi:10.1519/JSC.0b013e31817ae316. PMID:18815572.

Cohen, J. 1988. Statistical power analysis for the behavioural sciences. L. Erbraum Associates, Hillside, N.J., USA.

Condon, S.M., and Hutton, R.S. 1987. Soleus muscle electromyographic activity and ankle dorsiflexion range of motion during four stretching procedures. Phys. Ther. **67**: 24–30. PMID:3797473.

Costa, P.B., Ryan, E.D., Herda, T.J., Walter, A.A., Defreitas, J.M., Stout, J.R., and Cramer, J.T. 2013. Acute effects of static stretching on peak torque and the hamstrings-to-quadriceps conventional and functional ratios. Scand. J. Med. Sci. Sports, **23**: 38–45. doi:10.1111/j.1600-0838.2011.01348.x.

Costa, P.B., Herda, T.J., Herda, A.A., and Cramer, J.T. 2014. Effects of dynamic stretching on strength, muscle imbalance, and muscle activation. Med. Sci. Sports Exerc. **46**: 586–593. doi:10.1249/MSS.0000000000000138. PMID:24042312.

Cramer, J.T., Housh, T.J., Coburn, J.W., Beck, T.W., and Johnson, G.O. 2006. Acute effects of static stretching on maximal eccentric torque production in women. J. Strength Cond. Res. **20**: 354–358. doi:10.1519/00124278-200605000-00020. PMID:16686563.

Cramer, J.T., Housh, T.J., Johnson, G.O., Weir, J.P., Beck, T.W., and Coburn, J.W. 2007. An acute bout of static stretching does not affect maximal eccentric isokinetic peak torque, the joint angle at peak torque, mean power, electromyography, or mechanomyography. J. Orthop. Sports Phys. Ther. **37**: 130–139. doi:10.2519/jospt.2007.2389.

Cresswell, A.G., Löscher, W.N., and Thorstensson, A. 1995. Influence of gastrocnemius-muscle length on triceps surae torque development and electromyographic activity in man. Exp. Brain Res. **105**(2): 283–290. doi:10.1016/S0079-6123(08)63305-1. PMID:7498381.

Cronin, J., Nash, M., and Whatman, C. 2008. The acute effects of hamstring stretching and vibration on dynamic knee joint range of motion and jump performance. Phys. Ther. Sport, **9**: 89–96. doi:10.1016/j.ptsp.2008.01.003.

Curry, B.S., Chengkalath, D., Crouch, G.J., Romance, M., and Manns, P.J. 2009. Acute effects of dynamic stretching, static stretching, and light aerobic activity on muscular performance in women. J. Strength Cond. Res. **23**: 1811–1819. doi:10.1519/JSC.0b013e3181b73c2b. PMID:19675479.

Dadebo, B., White, J., and George, K.P. 2004. A survey of flexibility training protocols and hamstring strains in professional football clubs in England. Br. J. Sports Med. **38**(4):388–394. doi:10.1136/bjsm.2002.000044. PMID:15273168.

Dalrymple, K.J., Davis, S.E., Dwyer, G.B., and Moir, G.L. 2010. Effect of static and dynamic stretching on vertical jump performance in collegiate women volleyball players. J. Strength Cond. Res. **24**: 149–155. doi:10.1519/JSC.0b013e3181b29614. PMID:20042927.

Duncan, M.J., and Woodfield, L.A. 2006. Acute effects of warm-up protocol on flexibility and vertical jump in children. J. Exerc. Physiol. **9**: 9–16.

Ebben, W.P., Carroll, R.M., and Simenz, C.J. 2004. Strength and conditioning practices of National Hockey League strength and conditioning coaches. J. Strength Cond. Res. **18**: 889–897. doi:10.1519/00124278-200411000-00036. PMID:15574099.

Ebben, W.P., Hintz, M.J., and Simenz, C.J. 2005. Strength and conditioning practices of Major League Baseball strength and conditioning coaches. J. Strength Cond. Res. **19**: 538–546. PMID:16095401.

Eguchi, Y., Jinde, M., Murooka, K., Konno, Y., Ohta, M., and Yamato, H. 2014. Stretching versus transitory icing: which is the more effective treatment for attenuating muscle fatigue after repeated manual labor? Eur. J. Appl. Physiol. **114**: 2617–2623. doi:10.1007/s00421-014-2983-x. PMID:25151927.

Ekstrand, J., Gillquist, J., and Liljedahl, S.O. 1983. Prevention of soccer injuries. Supervision by doctor and physiotherapist. Am. J. Sports Med. **11**: 116–120. PMID:6346912.

Etnyre, B.L., and Lee, E.J. 1988. Chronic and acute flexibility of men and women using three different stretching techniques. Res. Quart. Exerc. Sport, **59**: 222–228. doi:10.1080/02701367.1988.10605507.

Ferber, R., Osternig, L., and Gravelle, D. 2002. Effect of PNF stretch techniques on knee flexor muscle EMG activity in older adults. J. Electromyogr. Kinesiol. **12**: 391–397. doi:10.1016/S1050-6411(02)00047-0. PMID:12223172.

Fletcher, I.M. 2010. The effect of different dynamic stretch velocities on jump performance. Eur. J. Appl. Physiol. **109**(3): 491–498. PMID:20162300.

Fletcher, I.M., and Anness, R. 2007. The acute effects of combined static and dynamic stretch protocols on fifty-meter sprint performance in track-and-field athletes. J. Strength Cond. Res. **21**: 784–787. PMID:17685686.

Fletcher, I.M., and Jones, B. 2004. The effect of different warm-up stretch protocols on 20 meter sprint performance in trained rugby union players. J. Strength Cond. Res. **18**: 885–888. PMID:15574098.

Fowles, J.R., Sale, D.G., and MacDougall, J.D. 2000. Reduced strength after passive stretch of the human plantar flexors. J. Appl. Physiol. **89**: 1179–1188. PMID:10956367.

Franco, B.L., Signorelli, G.R., Trajano, G.S., Costa, P.B., and de Oliveira, C.G. 2012. Acute effects of three different stretching protocols on the Wingate test performance. J. Sports Sci. Med. **11**: 1–7. PMID:24149116.

Gohir, S.A., Kozub, F.M., and Donnelly, A. 2012. Does acute static stretching reduce muscle power? J. Physiother. Sports Med. **1**: 104–114.

Guissard, N., and Duchateau, J. 2006. Neural aspects of muscle stretching. Exerc. Sport Sci. Rev. **34**: 154–158. doi:10.1249/01.jes.0000240023.30373.eb. PMID:17031252.

Gulick, D.T., Kimura, I.F., Sitler, M., Paolone, A., and Kelly, J.D. 1996. Various treatment techniques on signs and symptoms of delayed onset muscle soreness. J. Athl. Train. **31**(2): 145–152. PMID:16558388.

Hadala, M., and Barrios, C. 2009. Different strategies for sports injury prevention in an America's Cup yachting crew. Med. Sci. Sports Exerc. **41**: 1587–1596. doi:10.1249/MSS.0b013e31819c0de7. PMID:19568201.

Herda, T.J., Cramer, J.T., Ryan, E.D., McHugh, M.P., and Stout, J.R. 2008. Acute effects of static versus dynamic stretching on isometric peak torque, electromyography, and mechanomyography of the biceps femoris muscle. J. Strength Cond. Res. **22**: 809–817. doi:10.1519/JSC.0b013e31816a82ec. PMID:18438236.

Herda, T.J., Herda, N.D., Costa, P.B., Walter-Herda, A.A., Valdez, A.M., and Cramer, J.T. 2013. The effects of dynamic stretching on the passive properties of the muscle-tendon unit. J. Sports Sci. **31**: 479–487. doi:10.1080/02640414.2012.736632. PMID:23113555.

High, D.M., Howley, E.T., and Franks, B.D. 1989. The effects of static stretching and warm-up on prevention of delayed-onset muscle soreness. Res. Q. Exerc. Sport, **60**(4): 357–361. doi:10.1080/02701367.1989.10607463.

Hindle, K.B., Whitcomb, T.J., Briggs, W.O., and Hong, J. 2012. Proprioceptive neuromuscular facilitation (PNF): Its mechanisms and effects on range of motion and muscular function. J. Hum. Kinet. **31**: 105–113. PMID:23487249.

Hopkins, W.G. 2004. How to interpret changes in an athletic performance test. Sportscience, **8**: 1–7.

Hough, P.A., Ross, E.Z., and Howatson, G. 2009. Effects of dynamic and static stretching on vertical jump performance and electromyographic activity. J. Strength Cond. Res. **23**: 507–512. doi:10.1519/JSC.0b013e31818cc65d. PMID:19204571.

Huijing, P.A. 1999. Muscle as a collagen fiber reinforced composite: a review of force transmission in muscle and whole limb. J. Biomech. **32**(4): 329–345. doi:10.1016/S0021-9290(98)00186-9. PMID:10213024.

Jamtvedt, G., Herbert, R.D., Flottorp, S., Odgaard-Jensen, J, Havelsrud, K., Barratt, A., et al. 2010. A pragmatic randomised trial of stretching before and after physical activity to prevent injury and soreness. Br. J. Sports Med. **44**(14): 1002–1009. doi:10.1136/bjsm.2009.062232. PMID:19525241.

Johansson, P.H., Lindström, L., Sundelin, G., and Lindström, B. 1999. The effects of preexercise stretching on muscular soreness, tenderness and force loss following heavy eccentric exercise. Scand. J. Med. Sci. Sports, **9**(4): 219–225. PMID:10407930.

Kay, A.D., and Blazevich, A.J. 2008. Reductions in active plantarflexor moment are significantly correlated with static stretch duration. Eur. J. Sport Sci. **8**(1): 41–46. doi:10.1080/17461390701855505.

Kay, A.D., and Blazevich, A.J. 2009. Moderate-duration static stretch reduces active and passive plantar flexor moment but not Achilles tendon stiffness or active muscle length. J. Appl. Physiol. **106**(4): 1249–1256. doi:10.1152/japplphysiol.91476.2008. PMID:19179644.

Kay, A.D., and Blazevich, A.J. 2012. Effect of acute static stretch on maximal muscle performance: a systematic review. Med. Sci. Sports Exerc. **44**: 154–164. doi:10.1249/MSS.0b013e318225cb27. PMID:21659901.

Kay, A.D., Husbands-Beasley, J., and Blazevich, A.J. 2015. Effects of contract–relax, static stretching, and isometric contractions on muscle–tendon mechanics. Med. Sci. Sports Exerc. **47**: 2181–2190. doi:10.1249/MSS.0000000000000632. PMID:25668401.

Khamwong, P., Pirunsan, U., and Paungmali, A. 2011. A prophylactic effect of proprioceptive neuromuscular facilitation (PNF) stretching on symptoms of muscle damage induced by eccentric exercise of the wrist extensors. J. Bodyw. Mov. Ther. **15**(4): 507–516. doi:10.1016/j.jbmt.2010.07.006. PMID:21943625.

Knudson, D. 1999. Stretching during warm-up: do we have enough evidence? J. Phys. Educ. Rec. Dance, **70**: 24–28. doi:10.1080/07303084.1999.10605682.

Knudson, D., and Noffal, G. 2005. Time course of stretch-induced isometric strength deficits. Eur. J. Appl. Physiol. **94**: 348–351. doi:10.1007/s00421-004-1309-9. PMID:15711989.

Little, T., and Williams, A.G. 2006. Effects of differential stretching protocols during warm-ups on high-speed motor capacities in professional soccer players. J. Strength Cond. Res. **20**: 203–207. PMID:16503682.

Lund, H., Vestergaard-poulsen, P., Kanstrup, I.L., and Sejrsen, P. 1998. The effect of passive stretching on delayed onset muscle soreness, and other detrimental effects following eccentric exercise. Scand. J. Med. Sci. Sports, **8**(4): 216–221. doi:10.1111/j.1600-0838.1998.tb00195.x.

Maddigan, M.E., Peach, A.A., and Behm, D.G. 2012. A comparison of assisted and unassisted proprioceptive neuromuscular facilitation techniques and static stretching. J. Strength Cond. Res. **26**: 1238–1244. doi:10.1519/JSC.0b013e3182510611. PMID:22395273.

Magnusson, S.P., Simonsen, E.B., Aagaard, P., Dyhre-Poulsen, P., McHugh, M.P., and Kjaer, M. 1996*a*. Mechanical and physical responses to stretching with and without preisometric contraction in human skeletal muscle. Arch. Phys. Med. Rehabil. **77**: 373–378. doi:10.1016/S0003-9993(96)90087-8. PMID:8607762.

Magnusson, S.P., Simonsen, E.B., Aagaard, P., Sørensen, H., and Kjaer, M. 1996*b*. A mechanism for altered flexibility in human skeletal muscle. J. Physiol. **497**: 291–298. doi:10.1113/jphysiol.1996.sp021768. PMID:8951730.

Manoel, M.E., Harris-Love, M.O., Danoff, J.V., and Miller, T.A. 2008. Acute effects of static, dynamic, and proprioceptive neuromuscular facilitation stretching on muscle power in women. J. Strength Cond. Res. **22**: 1528–1534. doi:10.1519/JSC.0b013e31817b0433. PMID:18714235.

Matthews, P.B.C. 1981. Muscle spindles: their messages and their fusimotor supply. *In* The Nervous System: Handbook of Physiology. *Edited by* V.B. Brooks. American Physiological Society. pp. 189–288.

McHugh, M.P., and Cosgrave, C.H. 2010. To stretch or not to stretch: the role of stretching in injury prevention and performance. Scand. J. Med. Sci. Sports, **20**: 169–181. PMID:20030776.

McHugh, M., and Nesse, M. 2008. Effect of stretch on strength loss and pain after eccentric exercise. Med. Sci. Sports Exerc. **40**: 566–573. doi:10.1249/MSS.0b013e31815d2f8c. PMID:18379222.

McHugh, M.P., Tallent, J., and Johnson, C.D. 2013. The role of neural tension in stretch-induced strength loss. J. Strength Cond. Res. **27**(5):1327–1332. doi:10.1519/JSC.0b013e31828a1e73. PMID:23439335.

McKay, G., Goldie, P., Payne, W., and Oakes, B. 2001. Ankle injuries in basketball: injury rate and risk factors. Br. J. Sports Med. **35**(2): 103–108. doi:10.1136/bjsm.35.2.103. PMID:11273971.

McNair, P.J., Dombroski, E.W., Hewson, D.J., and Stanley, S.N. 2001. Stretching at the ankle joint: viscoelastic responses to holds and continuous passive motion. Med. Sci. Sports Exerc. **33**: 354–358. doi:10.1097/00005768-200103000-00003. PMID:11252058.

Mitchell, U.H., Myrer, J.W., Hopkins, J.T., Hunter, I., Feland, J.B., and Hilton, S.C. 2007. Acute stretch perception alteration contributes to the success of the PNF "contract-relax" stretch. J. Sport Rehabil. **16**: 85–92. PMID:17918696.

Mitchell, U.H., Myrer, J.W., Hopkins, J.T., Hunter, I., Feland, J.B., and Hilton, S.C. 2009. Neurophysiological reflex mechanisms' lack of contribution to the success of PNF stretches. J. Sport Rehab. **18**: 343–357. PMID:19827499.

Morse, C.I., Degens, H., Seynnes, O.R., Maganaris, C.N., and Jones, A.J. 2008. The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. J. Physiol. **586**: 97–106. doi:10.1113/jphysiol.2007.140434. PMID:17884924.

Murphy, J.R., Di Santo, M.C., Alkanani, T., and Behm, D.G. 2010*a*. Aerobic activity before and following short-duration static stretching improves range of motion and performance vs. a traditional warm-up. Appl. Physiol. Nutr. Metab. **35**: 679–690. doi:10.1139/H10-062. PMID:20962924.

Murphy, J.C., Nagle, E., Robertson, R.J., and McCrory, J.L. 2010*b*. Effect of single set dynamic and static stretching exercises on jump height in college age recreational athletes. Int. J. Exerc. Sci. **3**: 214–224.

Mutungi, G., and Ranatunga, K.W. 1998. Temperature-dependent changes in the viscoelasticity of intact resting mammalian (rat) fast- and slow-twitch muscle fibres. J. Physiol. **508**: 253–265. doi:10.1111/j.1469-7793.1998.253br.x. PMID:9490847.

Needham, R.A., Morse, C.I., and Degens, H. 2009. The acute effect of different warm-up protocols on anaerobic performance in elite youth soccer players. J. Strength Cond. Res. **23**: 2614–2620. doi:10.1519/JSC.0b013e3181b1f3ef. PMID:19910812.

Nelson, A.G., and Kokkonen, J. 2001. Acute ballistic muscle stretching inhibits maximal strength performance. Res. Q. Exerc. Sport, **72**: 415–419. PMID:11770791.

Nelson, A.G., Allen, J.D., Cornwell, A., and Kokkonen, J. 2001. Inhibition of maximal voluntary isometric torque production by acute stretching is joint-angle specific. Res. Q. Exerc. Sport, **72**(1): 68–70. PMID:11253322.

O'Connor, D.M., Crowe, M.J., and Spinks, W.L. 2006. Effects of static stretching on leg power during cycling. J. Sports Med. Phys. Fit. **46**: 52–56. PMID:16596099.

O'Hora, J., Cartwright, A., Wade, C.D., Hough, A.D., and Shum, G.L. 2011. Efficacy of static stretching and proprioceptive neuromuscular facilitation stretch on hamstrings length after a single session. J. Strength Cond. Res. **25**: 1586–1591. doi:10.1519/JSC.0b013e3181df7f98. PMID:21386723.

Orchard, J., Marsden, J., Lord, S., and Garlick, D. 1997. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. Am. J. Sports Med. **25**: 81–85. doi:10.1177/036354659702500116. PMID:9006698.

Palomero, J., Pye, D., Kabayo, T., and Jackson, M.J. 2012. Effect of passive stretch on intracellular nitric oxide and superoxide activities in single skeletal muscle fibres: influence of ageing. Free Radic. Res. **46**(1): 30–40. doi:10.3109/10715762.2011.637203.

Paradisis, G.P., Pappas, P.T., Theodorou, A.S., Zacharogiannis, E.G., Skordilis, E.K., and Smirniotou, A.S. 2014. Effects of static and dynamic stretching on sprint and jump performance in boys and girls. J. Strength Cond. Res. **28**: 154–160. doi:10.1519/JSC.0b013e318295d2fb. PMID:23591944.

Perrier, E.T., Pavol, M.J., and Hoffman, M.A. 2011. The acute effects of a warm-up including static or dynamic stretching on countermovement jump height, reaction time, and flexibility. J. Strength Cond. Res. **25**: 1925–1931. doi:10.1519/JSC.0b013e3181e73959. PMID:21701282.

Pope, R., Herbert, R., and Kirwan, J. 1998. Effects of ankle dorsiflexion range and pre-exercise calf muscle stretching on injury risk in Army recruits. Aust. J. Physiother. **44**: 165–172. doi:10.1016/S0004-9514(14)60376-7. PMID:11676730.

Pope, R.P., Herbert, R.D., Kirwan, J.D., and Graham, B.J. 2000. A randomized trial of preexercise stretching for prevention of lower-limb injury. Med. Sci. Sports Exerc. **32**: 271–277. doi:10.1097/00005768-200002000-00004. PMID:10694106.

Power, K., Behm, D., Cahill, F., Carroll, M., and Young, W. 2004. An acute bout of static stretching: effects on force and jumping performance. Med. Sci. Sports Exerc. **36**: 1389–1396. doi:10.1249/01.MSS.0000135775.51937.53. PMID:15292748.

Reis, E.F.S., Pereira, G.B., De Sousa, N.M.F., Tibana, R.A., Silva, M.F., Araujo, M., et al. 2013. Acute effects of proprioceptive neuromuscular facilitation and static stretching on maximal voluntary contraction and muscle electromyographical activity in indoor soccer players. Clin. Physiol. Funct. Imag. **33**: 418–422. PMID:23701400.

Robbins, J.W., and Scheuermann, B.W. 2008. Varying amounts of acute static stretching and its effect on vertical jump performance. J. Strength Cond. Res. **22**: 781–786. doi:10.1519/JSC.0b013e31816a59a9. PMID:18438240.

Rubini, E.C., Costa, A.L., and Gomes, P.S. 2007. The effects of stretching on strength performance. Sports Med. **37**: 213–224. doi:10.2165/00007256-200737030-00003. PMID:17326697.

Ryan, E.D., Cramer, J.T., Egan, A.D., Hartman, M.J., and Herda, T.J. 2008. Time and frequency domain responses of the mechanomyogram and electromyogram during isometric ramp contractions: a comparison of the short-time Fourier and continuous wavelet transforms. J. Electromyogr. Kinesiol. **18**: 54–67. doi:10.1016/j.jelekin.2006.09.003. PMID:17070700.

Samson, M., Button, D.C., Chaouachi, A., and Behm, D.G. 2012. Effects of dynamic and static stretching within general and activity specific warm-up protocols. J. Sports Sci. Med. **11**: 279–285. PMID:24149201.

Samuel, M.N., Holcomb, W.R., Guadagnoli, M.A., Rubley, M.D., and Wallmann, H. 2008. Acute effects of static and ballistic stretching on measures of strength and power. J. Strength Cond. Res. **22**: 1422–1428. doi:10.1519/JSC.0b013e318181a314. PMID:18714248.

Sekir, U., Arabaci, R., Akova, B., and Kadagan, S.M. 2010. Acute effects of static and dynamic stretching on leg flexor and extensor isokinetic strength in elite women athletes. Scand. J. Med. Sci. Sports, **20**: 268–281. PMID:19486475.

Sharman, M.J., Cresswell, A.G., and Riek, S. 2006. Proprioceptive neuromuscular facilitation stretching: mechanisms and clinical implications. Sports Med. **36**: 929–939. doi:10.2165/00007256-200636110-00002. PMID:17052131.

Shrier, I. 2004. Does stretching improve performance?: A systematic and critical review of the literature. Clin. J. Sport Med. **14**: 267–273. doi:10.1097/00042752-200409000-00004. PMID:15377965.

Siatras, T.A., Mittas, V.P., Mameletzi, D.N., and Vamvakoudis, E.A. 2008. The duration of the inhibitory effects with static stretching on quadriceps peak torque production. J. Strength Cond. Res. **22**: 40–46. doi:10.1519/JSC.0b013e31815f970c. PMID:18296954.

Simenz, C.J., Dugan, C.A., and Ebben, W.P. 2005. Strength and conditioning practices of National Basketball Association strength and conditioning coaches. J. Strength Cond. Res. **19**: 495–504. PMID:16095396.

Taylor, D.C., Brooks, D.E., and Ryan, J.B. 1997. Viscoelastic characteristics of muscle: passive stretching versus muscular contractions. Med. Sci. Sports Exerc. **29**(12): 1619–1624. doi:10.1097/00005768-199712000-00011. PMID:9432095.

Tidball, J.G., Lavergne, E., Lau, K.S., Spencer, M.J., Stull, J.T., and Wehling, M. 1998. Mechanical loading regulates NOS expression and activity in developing and adult skeletal muscle. Am. J. Physiol. **275**(1): C260–266. PMID:9688857.

Trajano, G.S., Seitz, L., Nosaka, K., and Blazevich, A.J. 2013. Contribution of central vs. peripheral factors to the force loss induced by passive stretch of the human plantar flexors. J. Appl. Physiol. **115**: 212–218. PMID:23661620.

Trajano, G.S., Seitz, L.B., Nosaka, K., and Blazevich, A.J. 2014. Can passive stretch inhibit motoneuron facilitation in the human plantar flexors? J. Appl. Phys. **117**(12): 1486–1492. PMID:25342705.

Van Mechelen, W., Hlobil, H., Kemper, H.C., Voorn, W.J., and de Jongh, H.R. 1993. Prevention of running injuries by warm-up, cool-down, and stretching exercises. Am. J. Sports Med. **21**: 711–719. doi:10.1177/036354659302100513. PMID:8238713.

Wallin, D., Ekblom, B., Grahn, R., and Nordenberg, T. 1985. Improvement of muscle flexibility: a comparison between two techniques. Am. J. Sports Med. **13**: 263–268. doi:10.1177/036354658501300409. PMID:4025678.

Waugh, C.M., Korff, T., Fath, F., and Blazevich, A.J. 2013. Rapid force production in children and adults: mechanical and neural contributions. Med. Sci. Sports Exerc. **45**(4): 762–771. doi:10.1249/MSS.0b013e31827a67ba. PMID:23190586.

Waugh, C.M., Korff, T., Fath, F., and Blazevich, A.J. 2014. Effects of resistance training on tendon mechanical properties and rapid force production in prepubertal children. J. Appl. Physiol. **117**(3): 257–266. doi:10.1152/japplphysiol.00325.2014. PMID:24903920.

Weir, D.E., Tingley, J., and Elder, G.C. 2005. Acute passive stretching alters the mechanical properties of human plantar flexors and the optimal angle for maximal voluntary contraction. Eur. J. Appl. Physiol. **93**(5-6): 614–623. doi:10.1007/s00421-004-1265-4. PMID:15578204.

Whatman, C., Knappstein, A., and Hume, P. 2006. Acute changes in passive stiffness and range of motion post-stretching. Phys. Ther. Sport, **7**: 195–200. PMID:21663832.

Winke, M.R., Jones, N.B., Berger, C.G., and Yates, J.W. 2010. Moderate static stretching and torque production of the knee flexors. J. Strength Cond. Res. **24**: 706–710. doi:10.1519/JSC.0b013e3181c7c557. PMID:20145556.

Yamaguchi, T., Ishii, K., Yamanaka, M., and Yasuda, K. 2007. Acute effects of dynamic stretching exercise on power output during concentric dynamic constant external resistance leg extension. J. Strength Cond. Res. **21**: 1238–1244. doi:10.1519/00124278-200711000-00044. PMID:18076260.

Young, W.B. 2007. The use of static stretching in warm-up for training and competition. Int. J. Sports Physiol. Perf. **2**: 212–216. PMID:19124908.

Young, W.B., and Behm, D.G. 2003. Effects of running, static stretching and practice jumps on explosive force production and jumping performance. J. Sports Med. Phys. Fit. **43**: 21–27. PMID:12629458.

Young, W., and Elliott, S. 2001. Acute effects of static stretching, proprioceptive neuromuscular facilitation stretching, and maximum voluntary contractions on explosive force production and jumping performance. Res. Q. Exerc. Sport, **72**(3): 273–279. PMID:11561392.

Zourdos, M.C., Wilson, J.M., Sommer, B.A., Lee, S.R., Park, Y.M., Henning, P.C., et al. 2012. Effects of dynamic stretching on energy cost and running endurance performance in trained male runners. J. Strength Cond. Res. **26**: 335–341. doi:10.1519/JSC.0b013e318225bbae. PMID:22266545.