The effects of acute static and dynamic stretching on spring-mass leg stiffness.

Running Head: Stretching and leg stiffness

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Abstract

Objective: This study investigated the effect of brief static and dynamic stretching on spring-mass leg stiffness in a vertical bilateral hopping task.

Method: 38 men and 18 women were randomly assigned to either a natural (NAT; *n* = 27), or maximal (MAX; *n* = 29) hopping group. NAT bounced at their self-selected stiffness and MAX were instructed to bounce as stiffly as possible. Hopping was performed at 2.2 Hz on a force plate. After each of four treatment conditions (no stretch, 30 s stretch, multiple (4 ×) 30 s stretch, and dynamic stretch), subjects completed three × 30 s bouts (2 minute rest periods) of hopping, in a counterbalanced crossover design. Stretches were performed on: gluteals, hamstrings, quadriceps and calves. Spring-mass leg stiffness was calculated as the ratio of peak vertical force to vertical displacement during ground contact.

Results: The results revealed that men displayed greater leg stiffness than women (mean difference: 6.04 $kN \cdot m^{-1}$; 95% likely range: 1.94 – 10.13 $kN \cdot m^{-1}$), and that MAX produced higher stiffness values than NAT (mean difference: 10.93 $kN \cdot m^{-1}$; 95% likely range: 6.84 – 15.03 $kN \cdot m^{-1}$). Although there were no significant effects of treatment (p = 0.85) or time (p = 0.54) on leg stiffness, there was a significant treatment × time interaction (p = 0.015). Nevertheless, *post hoc* analyses were unable to identify where those differences were.

Conclusion: Relative to control, the results of this study showed that brief static stretching or non task-specific dynamic stretching does not affect spring-mass leg stiffness during vertical bilateral hopping.

Key words: Flexibility; spring-mass; vertical stiffness; warm-up.

1. Introduction

The act of stretching muscles has become common in the field of athletic development. The benefits of stretching on flexibility have been researched for some time, with a consensus of positive acute and chronic effects (Behm et al., 2016; Sharman et al., 2006). With regards to the effects of stretching on injury prevention; whilst there appear to be some indications that the risk of injury may be reduced under specific conditions (Woods et al., 2007), there is insufficient evidence to make strong recommendations to athletes (Thacker et al., 2004; Weldon & Hill, 2003). The impact of stretching on subsequent performance has been considered with some evidence of chronic performance enhancement (Kokkonen et al., 2007; Kokkonen et al., 2010) and some of acute benefits following routines containing dynamic stretching (DS) (McMillian et al., 2006). However, there has also been a substantial amount of research highlighting acute decrements in function following static stretching (SS) (Behm et al., 2001; Cramer et al., 2004; Fowles et al., 2000; Zakas et al., 2006a) with proposed mechanisms including reduced activation (Behm, et al., 2001; Power et al., 2004) and increased muscle compliance (Power et al., 2004). However, these findings are not unequivocal, and variations in outcome appear dependant on several factors including the stretching technique (Woolstenhulme et al., 2006), the intensity of the stretch (Behm & Kibele, 2007), the duration of the stretch (Zakas et al., 2006a; Zakas et al., 2006b), the interim time between stretching and performance (Brandenburg et al., 2007), the preconditioning of the participants (Chaouachi et al., 2008), and the characteristics of the performance measure (Manoel et al., 2008). Nevertheless, these negative effects of SS on athletic performance have led to recommendations for the removal of SS from pre-performance routines (Knudson, 2010), with such recommendations making their way into coach education pathways (e.g. UK Athletics).

The most consistent evidence of detrimental effects from SS has come from protocols involving the use of prolonged stretches (>150 s), with performance assessed either isokinetically (Behm et al., 2001; Cramer et al., 2004; Fowles et al., 2000) or by some sport-specific test of power (Behm et al., 2016). However, when shorter (approximately 30-60 s) stretch periods have been utilised, there is far less agreement (Behm et al., 2004; Power et al., 2004; Yamaguchi & Ishii, 2005). Factors such as the inclusion of intermediary practice activities, or the use of complex multi-joint stretch-shortening cycle based performance measures, may explain these inconsistent findings (Chaouachi et al., 2010; Fletcher & Anness, 2007; Fletcher & Jones, 2004). Nevertheless, these factors are important since SS use in a sport setting typically involves brief stretches prior to some form of more specific interim preparatory and often potentiating activity. Since detrimental SS effects appear to largely dissipate over a period of around 1 hour (Brandenburg et al., 2007), and are, to some extent, proportional to the period of stretch utilised (Simic et al., 2013) it may well be the case that detrimental effects of SS do not carry over to performance in many athletic settings.

Interpretation of the literature, as it pertains specifically to stretching, is further confounded when stretching protocols are inconsistently described and combined with other warm-up activities (Opplert and Babault, 2018). Comparisons between SS and DS are problematic when DS protocols contain some specific skill rehearsal or activation relating to the performance task (Di Cagno et al., 2010; Fletcher & Anness, 2007; Fletcher & Jones, 2004). Additional difficulties arise when the interim period between stretch and performance is not stated and when cohorts are small. In some cases, negative effects might also be the outcome of interference with athletes' normal preparatory routines in the final minutes before performance (Kistler et al., 2010) rather than due to the stretch itself. Some recent studies controlling for these factors have indeed found no detrimental effects of SS on subsequent athletic performance (Chaouachi et al., 2010). Bearing these issues in mind, it may be the case that blanket recommendations to remove static stretching from preparatory routines might be premature or require significant caveats.

The spring-mass model has been utilised for some time in biomechanics research and is considered a valid model for the study of running/bouncing gaits (Günther & Blickhan, 2002; Seyfarth et al., 2002). Leg stiffness, as assessed through the model is thought to be related to optimisation of stored elastic energy usage (Farley et al., 1991) and has been linked to important performance factors such as running economy (Dalleau et al., 1998; Heise & Martin, 1998), running speed (Bret et al., 2002; Chelly & Denis, 2001), ground contact time (Arampatzis et al., 2001), and injury risk (Blackburn et al., 2004; Granata et al., 2000; Williams et al., 2004). More significantly, when utilised in a simple vertical bilateral hopping task, it presents an illustration of an athlete's ability to utilise a stretch-shorten cycle effectively. Leg stiffness complements the typical isokinetic data normally used to create controllable *in vivo* models for the study of concentric or eccentric muscle function in isolation. Further, relative to stretch-shorten-cycle tasks such as sprinting, its simple and unfamiliar nature reduces the influence of some potential confounding factors such as issues of control during complex movement tasks, effects of change in the range of movement, perceived risk and apprehension from athletes who have not completed their typical warm-up routine, and placebo effects from athletes who believe SS will make them acutely less powerful in familiar explosive tasks.

Control of maximal and submaximal hopping tasks differs depending on the task constraints. Farley and Morgenroth (1999) highlighted the ankle as the primary mediator of function in bilateral hopping, but ankle and knee torsional stiffness varied substantially between preferred height and maximal height hopping. The extent and rate of muscle activation and reflex input (Hobara et al., 2007), and changes in the characteristics of elastic energy storage (Ishikawa & Komi, 2004) required to achieve these joint torsional stiffness changes, offers potential for differentiable effects from stretching routines when comparing leg stiffness in preferred and maximal hopping tasks.

The aim of the present study was therefore to address the aforementioned methodological issues to consider the influence of brief SS and non-rehearsal based DS on leg stiffness in a bilateral hopping task with both preferred and maximal levels of stiffness. It was hypothesised that both brief static and non-rehearsal based dynamic stretching would not change leg stiffness and that repeated static stretching would reduce stiffness relative to no stretch control.

2. Methods

2.1. Experimental overview

Participants were randomly assigned to one of two groups. One group (MAX; *n* = 29) were assessed in the bilateral hopping task, having been given the instructions ‘to be as stiff as possible’, ‘to spend as little time on the ground as possible’ and ‘to remain in time with the metronome’; the second group (NAT; *n* = 27) were assessed having been given the instruction ‘to bounce naturally in time with the metronome’. Each group completed the hopping task following four treatment conditions one week apart in a counterbalanced crossover design. The four treatment conditions were single static stretch (SS), multiple static stretch (SM), dynamic stretch (DS) and no stretch (NO). Participants were instructed to refrain from strenuous activity in the 24-hour period preceding each trial, to avoid eating in the hour before testing, and to wear the same footwear to each trial. All participants attended a familiarisation session and were introduced to the stretching and assessment protocols, and practiced the bouncing task.

2.2. Participants

56 (38 men, 18 women) undergraduate sport science students volunteered for the study which was approved by St Mary’s University Ethics Committee. For inclusion, participants were required to regularly complete a minimum of 1 hour of exercise per week; most subjects completed at least 3 hrs of exercise per week. Participants were excluded from the study if they reported any musculo-skeletal injury to the lower limbs, back or abdomen. Prior to commencement of the study, all participants were informed of the test procedures before providing written informed consent. Acceptable participant numbers were based on previous studies that detected changes in bounce stiffness with between 7 (Farley et al., 1991) and 14 (Hobara et al., 2007) participants, and sample

size calculations indicating a requirement for approximately 40 subjects. Mean ± *SD* for age, height and body mass of the participants are presented in Table 1.

Table 1. Participant characteristics. Values are means ± standard deviation.

	Age (years)	**Height (cm)**	**Body Mass (kg)**
Gender			
Male (n = 38)	21.5 ± 2.9	181.0 ± 6.5*	79.0 ± 13.4*
Female (n = 18)	21.3 ± 3.5	167.2 ± 6.9	63.4 ± 11.5
Group			
NAT (n = 27)	21.9 ± 3.7	177.6 ± 8.1	77.0 ± 16.4
MAX (n = 29)	20.9 ± 2.2	175.1 ± 10.3	70.5 ± 12.3

Note: NAT = natural bouncing group; MAX = maximal stiffness bouncing group; * represents a significant effect of gender ($p < 0.05$).

2.3. Procedures

2.3.1. Static stretch conditions (SS and SM)

In the SS trial, participants stretched the following muscle groups of both legs: gluteals, hamstrings, quadriceps-hip flexors, and the triceps surae complex. Each stretch was held for 30 s at a point of mild discomfort, with 15 s recovery between stretches. A single stretch was applied to each muscle group on each limb for the SS condition, with four repeats of the protocol used for the SM condition. This represented stretch volumes above and below the two 30 s stretch volume suggested to alter musculotendinous stiffness of the plantar flexors (Ryan et al., 2009). Stretch positions are illustrated in Figure 1.

2.3.2. Dynamic stretch condition (DS)

Dynamic stretches were generated by an active contraction of the antagonist muscle group, with the limb starting in a neutral position and then dynamically moved to and from a position of stretch. The same muscle groups were stretched as in the SS condition; positions being illustrated in Figure 2. Each DS was repeated 15 times, taking approximately 30 s to complete each set. Dynamic activities did not involve rehearsal of the task utilised for testing.

2.3.3. No stretch condition (NO)

In the NO condition participants remained seated for a period of 5 minutes prior to testing.

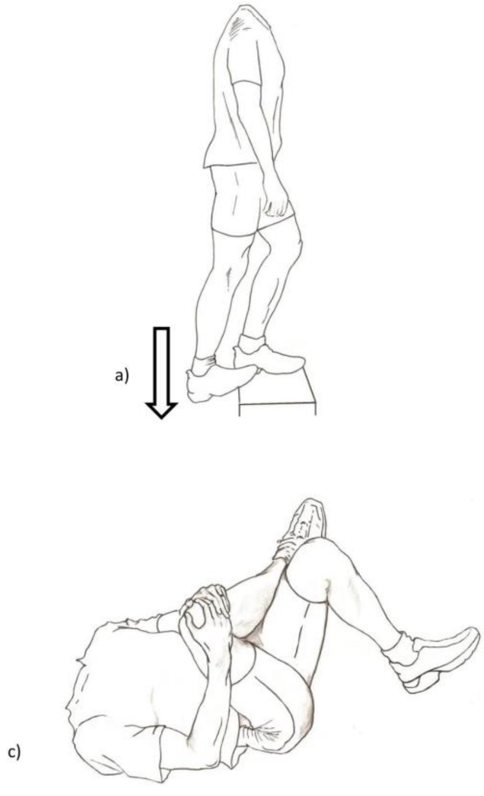

Figure 1. Static stretching positions for the triceps surae complex (a), hamstrings (b), gluteals (c), and quadriceps-hip flexors (d). Each stretch was held for 30 s, with 15 s recovery between stretches.

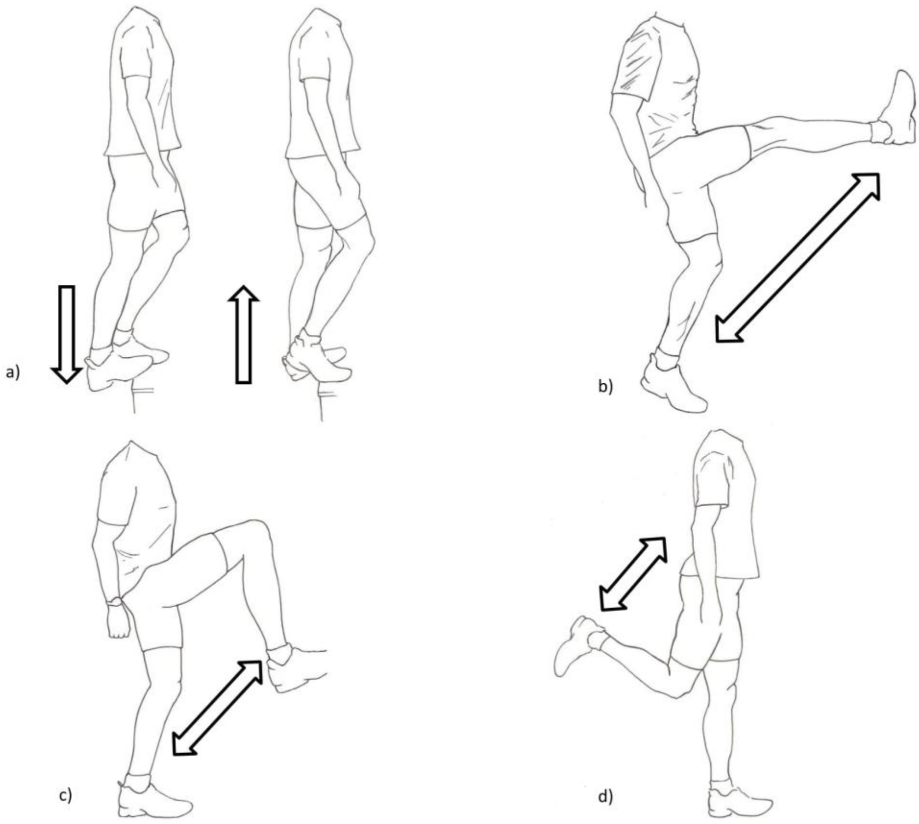

Figure 2. Dynamic stretching positions for triceps surae complex (a), hamstrings (b), gluteals (c), and quadriceps-hip flexors (d). Each stretch was repeated 15 times, taking approximately 30 s to complete each set.

2.3.4. Leg stiffness protocol

After completion of the stretching protocols, participants rested for 1 to 3 minutes prior to completing the hopping task. For the assessment of leg stiffness, participants completed 3 × 30 s bouts of bilateral vertical hopping on a 600 mm × 900 mm force plate (Model 9287BA; Kistler Instruments Ltd., Hampshire, UK), with data sampled at a frequency of 1000 Hz. Each bout was separated by 2 minutes of seated rest. All participants hopped at a frequency of 2.2 Hz, to approximate the preferred frequency for vertical hopping in humans (Farley et al., 1991) with arms resting by their side. The bouncing frequency was regulated by a custom computer-generated digital metronome. Prior to each trial participants were reminded of the instructions pertaining to the nature of their hopping task (MAX or NAT) and to retain foot contacts in time with the metronome.

2.4. Data analysis

Leg stiffness was calculated from vertical spring stiffness (Equation 1.), where k is the stiffness value on a specific bounce, F_{max} is the peak vertical ground reaction force generated on that bounce and ΔL is the centre of mass (COM) vertical displacement during ground contact on that bounce. ΔL was calculated from the second differential of the vertical acceleration (after correction for bodyweight) (Cavagna, 1985; Farley & Morgenroth), as the COM displacement between point of ground contact (taken when GRF exceeded 50 N) and the point of minimum COM height. Bounces were ignored for the first 5 s of each trial to allow subjects to settle into the bouncing rhythm. Following this period, bounces were only accepted as valid if they fell within 5% of the of the assigned 2.2 Hz frequency as bounce frequency is important for the reliability of stiffness measurement (Hobara et al., 2007). Leg stiffness was taken as the mean of the first five consecutive valid bounces in each bout following the initial 5 s cutoff period. Variability in leg stiffness across each five-bounce sequence was determined as a coefficient of variation.

Equation 1. $k_{leg} = F_{max} / \Delta L$

2.5. Statistical analyses

All statistical analysis was carried out using the Statistical Package for the Social Sciences (SPSS Inc., Chicago, IL). Measures of centrality and spread are presented as means ± standard deviation. Independent *t*-tests were used to compare groups on descriptive variables (age, height, body mass, and body fat). The effects of gender, group, treatment, and time (exercise bout) on measures of leg stiffness, coefficient of variation and the bounce number on which a valid bounce series began were evaluated using four-way mixed ANOVA. α was set at 0.05 for all analyses. Significant interactions were followed-up using *post hoc* tests with Bonferroni adjustments for multiple comparisons. The above analyses provided 95% confidence limits for all estimates.

3. Results

3.1. Group characteristics

Descriptive statistics separated by group and gender are presented in Table 1. There were no significant differences ($p \geq 0.05$) in any descriptive variables for the NAT and MAX groups. Between genders however, height and body mass were both significantly different ($p < 0.05$).

3.2. Leg stiffness

The effects of gender, group, treatment, and time on leg stiffness are presented in Figure 3. There was a significant effect of gender on leg stiffness, with men showing higher values than women (mean difference: 6.04 $kN \cdot m^{-1}$; 95% likely range: 1.94 – 10.13 $kN \cdot m^{-1}$). There was also a significant effect of group on leg stiffness, with MAX showing higher values than NAT (mean difference: 10.93 $kN \cdot m^{-1}$; 95% likely range: 6.84 – 15.03 $kN \cdot m^{-1}$). Although there were no significant effects of treatment ($p = 0.85$) or time ($p = 0.54$) on leg stiffness, there was a significant treatment × time interaction (p

= 0.015). Nevertheless, *post hoc* analyses were unable to identify where those differences were (Figure 4). There were no significant interaction effects for any of the remaining comparisons.

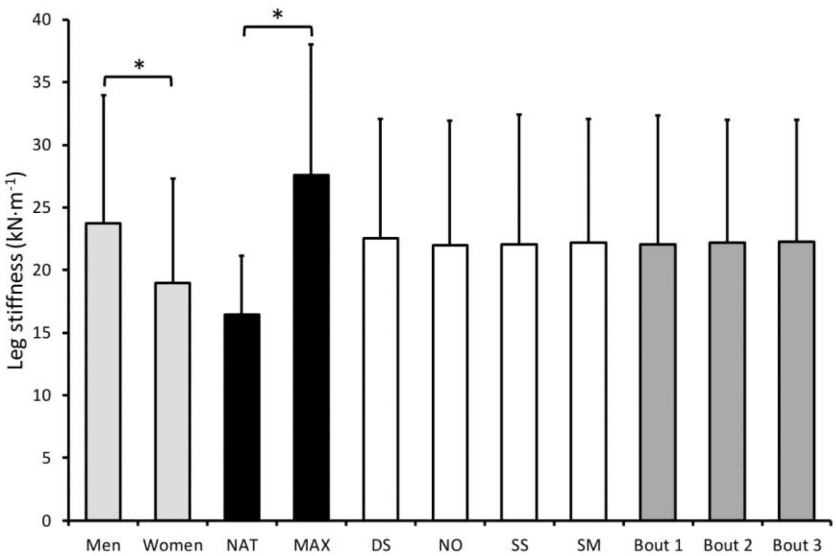

Figure 3. Leg stiffness scores for groups by gender (38 men, 18 women), group (NAT = 27, MAX = 29), treatment (DS, NO, SS, SM; n = 56 for all), and time (Bouts 1, 2, & 3; n = 56 for all). Values are means, bars are standard deviations. Note: NAT = natural bouncing group, MAX = bouncing with maximal stiffness group, DS = dynamic stretch treatment, NO = no stretch treatment, SS = single static stretch treatment, SM = multiple static stretch treatment; * $p < 0.05$.

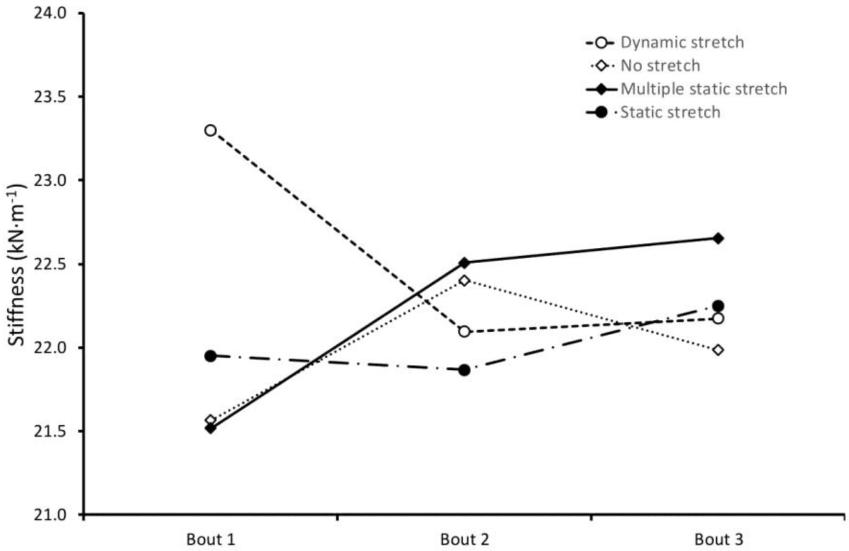

Figure 4. Leg stiffness scores across time for each of the four stretch treatments (n = 56 in all cases). Values are means. Standard deviations are omitted for clarity, but values ranged from 9.03 – 10.85 $kN \cdot m^{-1}$.

3.3. Bounce number and stiffness variability

The number of bounces taken prior to a continuous series of valid bounces, sufficient for stiffness calculation, may have implications relating to fatigue across trials. Mean and standard deviation values for the first bounce utilised in calculations along with the coefficient of variation for the subsequent sequence of bounces used to determine leg stiffness are presented in Table 2. There were no significant effects of gender, group, treatment, time, or any of the associated interactions on bounce number or coefficient of variation.

Table 2. Bounce number on first bounce of accepted valid bounce series and the coefficient of variation of the corresponding five bounce sequence of leg stiffness values. Values are means ± standard deviation.

	Gender		Group		Stretch				Bout		
	Male	*Female*	*NAT*	*MAX*	*DS*	*NO*	*SS*	*SM*	*1*	*2*	*3*
Bounce no.	15.5 ± 4.4	15.3 ± 4.0	16.1 ± 4.4	14.9 ± 4.1	15.6 ± 4.3	15.3 ± 4.3	15.4 ± 4.2	15.6 ± 4.4	15.2 ± 4.4	15.4 ± 4.0	15.9 ± 4.6
CV (%)	8.6 ± 4.2	8.9 ± 4.4	8.5 ± 3.9	8.9 ± 4.5	8.4 ± 4.7	8.9 ± 3.8	8.5 ± 3.6	9.0 ± 4.7	8.5 ± 4.1	8.8 ± 4.3	8.8 ± 4.4

Note: NAT = natural bouncing group; MAX = maximal stiffness bouncing group; DS = dynamic stretching condition; NO = no stretching condition; SM = multiple static stretching condition; SS = static stretching condition; CV = coefficient of variation.

4. Discussion

The main aim of this study was to examine the effect of static and dynamic stretching on leg stiffness in a bilateral, vertical hopping task. Relative to control, there was no significant effect of stretching protocols on leg stiffness. Values of leg stiffness for the NAT group were comparable with previous research (Serpell et al., 2012). Also in agreement with previous data (Granata et al., 2002) was the finding that men exhibited higher absolute levels of leg stiffness than women, at least when expressed in absolute terms, and presumably due to the higher levels of absolute strength typically seen in men. The MAX group were able to exhibit stiffness scores which were significantly higher (~ 60%) than those of the NAT group, which was taken as confirmation of the independence of the two test conditions and of the plasticity of the stiffness variable to intervention effects.

A trend in the literature evidencing performance decrements following prolonged SS has prompted discussion as to the mechanisms of outcomes of stretching protocols. Studies have highlighted both mechanical (e.g. Herda et al., 2008) and neurological changes following stretching (Behm et al., 2016) which, might explain the significant treatment × time interaction on leg stiffness. Although *post hoc* tests were unable to locate significant differences between treatments at each time point, the first bounce trial exhibited a trend towards increased stiffness following DS (Figure 4), possibly resulting from a neural stimulus offered through this protocol. The DS protocol might offer less substantial changes in muscle viscosity (Mutungi & Ranatunga, 1998) and elastic pliability. In line with this explanation is the ensuing trend for reductions in stiffness in the later trials following the DS protocol which might represent a mild fatigue effect following the early increased muscle activation. The other notable trend that may explain the significant treatment × time interaction effect was that of the progressive increase in stiffness across trials following the SM protocol. This might be explained as the appearance of a mild potentiation effect becoming visible alongside reduced muscle viscosity over that likely in the other three protocols. Additionally, there might be a progressive dissipation of a subtle inhibitory effect of repeated static stretching, in line with the body of research highlighting the potential for detrimental stretch outcomes beyond 60s of static stretch (Behm et al., 2016). Regardless, the collapse by bouts 2 and 3 of any divergence seen at bout 1 implies an absence of impact on performance where intermediary task specific activity will take place.

This study showed that both single and repeated bouts of brief (30 s) static stretching had no effect on a multi-joint stretch-shorten-cycle task. This absence of performance decrements may be due solely to the brevity of the stretches used; however, the multiple static stretch protocol here totalled 120 s of stretching per muscle group, a timeframe previously highlighted in systematic reviews to have an effect on isokinetic performance and in functional tasks (Behm et al., 2016; Kay & Blazevich, 2012). Moreover, although there are several contradictory reports, static stretches < 60 s are reported to result in a small reduction in some types of performance (Behm et al., 2016). With this in mind, it seems that abbreviating stretch periods might not be entirely sufficient to avoid negative performance outcomes, and as such do not sufficiently explain the current findings. A second possibility to explain the absence of performance decrements from SS is that in a multi-joint stretch-shorten-cycle task there is sufficient redundancy and plasticity in the route to achieving the overall performance outcome required. This implies that the functional capacity of individual stretched prime movers may not always be the limiting determinant of performance; as such, small reductions in stretched muscle function might not be material in more complex motor tasks. Whilst this assertion is not supported by studies that have previously highlighted SS-related losses in jump and sprint performance, it should be noted that studies presenting these findings have mostly utilised longer (≥ 60 s) stretch periods or implemented stretches immediately prior to the performance measure (Behm et al., 2016). As such, the stretch period and task together go some way to explain the current result.

A further consideration is that the current body of literature is subject to the influence of participant perceptions since blind interventions and placebo controls are difficult to implement in this area. Popular coaching has been heavily permeated by references to early studies demonstrating losses in performance following stretching (Cornwell et al., 2001; Cornwell et al., 2002; Fowles et al., 2000). Athletes also have an expectation of the need for their normal warm-up routine. Acute stretching interventions may impact performance where this represents a substantial departure from an athlete’s normal preparatory routine (Young & Behm, 2002). Whilst negative stretch effects have been shown to largely dissipate over the course of around 1 hour (Brandenburg et al., 2007), the present study showed no effect despite stretching immediately prior to performance. This could have been in part due to the unfamiliarity of the bouncing task and with it a removal of expectation for a normal preparatory process, or recognition of how performance would be defined, quantified, or affected.

The general finding here of no effect on a multijoint stretch-shorten-cycle task is not in agreement with the typically demonstrated positive effects following DS in skills such as sprinting and vertical jumping (Behm et al., 2016). One explanation for this difference is the general interchangeable use of the terms warm-up and stretching, particularly with regard to activities labelled as dynamic. For example, many studies (Fletcher & Annes, 2007; Fletcher & Jones, 2004) have compared the use of SS with DS, where DS activities represent additional specific warm-up activities including elements of skill rehearsal, active warming, and possibly an element of potentiation. In some cases, SS is compared to what is virtually a complete specific warm-up routine (McMillian et al., 2006). Whilst this has been proposed by authors as a possible explanation for DS benefits it confounds comparisons of the relevant elements of the nature of the stretch. Additionally studies that have included interim specific preparatory activities (Chaouachi et al., 2010), as would generally be the case in sports settings, or used dynamic stretches that do not additionally act as specific warm-up activities (Chaouachi et al., 2010), have not found negative outcomes from SS or positive outcomes from DS. The trend for an enhanced first trial immediately following DS in this study highlights the potential for a mild initial benefit in this case, but it appears unlikely this would progress into performance in an applied setting where longer interim periods and other specific practice would be included. Clearly the recommendation for inclusion of dynamic specific preparatory activities is strong; however, the evidence for the stretch specific element of DS being advantageous or SS being detrimental in an applied setting is not conclusive.

5. Limitations

Participants were recreationally active, many regularly participating in sports, but were not highly-trained athletes. Care should be taken with the application to findings in more athletic populations. In addition, the present study considered the effect of only the stretch component of pre-activity routines and therefore should not be taken to characterise the potential effects of a wider more complete preparatory routine.

6. Conclusions

The results of the present study do not fully conform to the general trend of findings regarding the impact of DS and SS on performance. It would appear that the stretch component of DS does not offer clear acute performance benefits. Potential negative effects of SS are not evident here, and should there be any, they would appear to dissipate rapidly following the inclusion of specific dynamic activity.

7. Clinical Relevance

- The potential benefits of DS, as demonstrated elsewhere, warrants their inclusion in preparatory routines, but any performance benefits do not appear to derive from the altered format of stretching.
- Although SS has not been shown to acutely enhance performance, an absence of negative impact means that it may still be indicated where extreme levels of flexibility are required or where coaches and athletes believe that time spent on SS has other benefits such as in controlling arousal and focus in the hours prior to competition.

Ethical approval

This study was approved by St Mary's University Ethics Committee.

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Conflicts of Interest

No conflict of interests have been reported by the authors or by any individuals in control of the content of this article.

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