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Research article

The Acute Effects of Antagonist Static Stretching on Agonist Performance

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Abstract

Stretching the antagonist muscle to enhance agonist performance has gained considerable attention. However, most studies have focused on one stretching duration. Hence, the aim of this study was to compare varying durations (40-, 80-, and 120-seconds) of antagonist (dorsiflexors) static stretching (SS) on agonist (plantar flexors: PF) muscle performance. In this randomized crossover study, 16 participants (six females) underwent four sessions (40-, 80-, 120-s dorsiflexors SS and control), with pre- and post-intervention measurements of slow (60^0/s) and fast (240^0/s) PF isokinetic, isometric peak torque, total work, stiff leg drop jump (SDJ) performance (height, reactive strength index (RSI) and peak power), and tibialis anterior and soleus electromyography (EMG). Dorsiflexors SS protocol involved 1x40-s (40-s), 2x40-s (80-s), and 3x40-s (120-s). There were no significant pre- to post-intervention changes in any parameter. A main effect for time demonstrated an overall decrease in fast ($p < 0.0001$, 5.9%, $d = 0.24$) and slow ($p = 0.05$, 6.6%, $d = 0.24$) isokinetic peak torque, total work ($p = 0.02$, 5.1%, $d = 0.20$) and all SDJ measures (SDJ height: $p = 0.02$, 2.7%, $d = 0.15$, RSI: $p < 0.0001$, 5.9%, $d = 0.23$, peak power: $p = 0.002$, 4.4%, $d = 0.22$). Soleus EMG decreased from pre- to post-SS after 120-s in both isometric ($p = 0.002$, 13.6%, $d = 0.73$) and slow isokinetic ($p = 0.002$, 12.3%, $d = 0.91$) peak torque as well as 80-s with slow isokinetic peak torque ($p = 0.02$, 6.6%, $d = 0.75$). In summary, different durations of dorsiflexors SS (40-s, 80-s, 120-s) did not significantly influence PF performance. However, deficits associated with a main effect for time suggested possible testing effects as detected with the control condition.

Key words: Co-contractions, co-activation, dorsiflexors, plantar flexors, peak torque, electromyography.

Introduction

Stretch training is a popular form of exercise that has been shown to acutely and chronically enhance joint range of motion (ROM) (Behm et al., 2013; 2023; Konrad et al., 2024). Early claims of improved performance with static stretching (SS) suggested that increased flexibility permitted a greater joint ROM due to a more compliant musculotendinous tissue to decrease the resistance to movement through a full ROM (Behm and Chaouachi 2011; Behm 2018; Bryant et al., 2023).

However, over the last 25 years, acute bouts of prolonged SS (>60-s per muscle group) have been reported to impair subsequent performance (e.g., force, torque, power, balance, muscle activation) (Behm and Chaouachi 2011; Behm et al., 2001; 2016; 2021; Chaabene et al., 2019; Cornwell et al., 2002; Fowles et al., 2000; Kay and Blazevich, 2012; Shrier, 2004). Similarly, a meta-analysis by Simic et al. (2013) reported that the smallest performance deficits were observed with stretch duration of ≤45-s. A recent meta-analysis (Warneke and Lohmann, 2024) demonstrated high magnitude effect size static stretch-induced impairments for 60-s stretching durations compared to passive controls, but trivial to small deficits when opposed to active controls. Overall, they found that stretching did not impair athletic performance in general (when combining comparisons to both passive and active controls) and actually provided a positive but trivial magnitude effect on subsequent jump performance. Hence, the duration of stretching the targeted muscle and the inclusion of other activities can modulate the degree of stretch-induced performance deficits.

Inappropriate timing or the extent of antagonist muscle co-contractile activity can also have negative impacts on agonist muscle performance by providing resistance to the intended movement (Behm and Sale, 1996; Beltman et al., 2003; Smith, 1981). The simultaneous contraction and activation of the agonist and antagonist is commonly referred to as "coactivation" or "co-contraction" (Folland and Williams, 2007; Tillin et al., 2011), which can hinder the agonist from achieving its full force or power output (Baratta et al., 1988; Draganich et al., 1989) by providing a "braking effect" (Dal Maso et al., 2012; Sandberg et al., 2012). Decreasing co-contractile neuromuscular activation (Fowles et al., 2000) and reducing musculotendinous unit compliance (Fowles et al., 2000; Kallerud and Gleeson, 2013) may attenuate its antagonist counteracting force improving agonist force output. However, the findings of antagonist SS are contradictory. Since prolonged SS of a target (agonist) muscle for more than 60-s can induce force, power, and neuromuscular activation deficits (Warneke and Lohmann 2024; Behm et al., 2016; 2021; Chaabene et al., 2019; Simic et al. 2013, Kay and Blazevich 2012), similar durations of antagonist stretching might also decrease the co-contractile resistance to intended movement or agonist contractions. Therefore, the benefits of agonist and antagonist SS must be considered from a dose-response point of view.

Several investigations have employed varying antagonist SS durations and protocols to showing positive effects of antagonist SS effects on agonist muscle performance. Elliott and Massey (Elliott and Massey, 2020) revealed a significant increase in bench press maximum power with 30-s of SS targeting shoulder adductors and protractors ($d = 1.33$). Additionally, performing 3 or 4 sets of 30-s (90 - 120-s) of SS on hip flexors, knee flexors,

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and/or dorsiflexors, which are antagonist muscles during vertical jumping (VJ), led to generally small to moderate magnitude increases VJ height (Sandberg et al., 2012, d = 0.09; Wakefield and Cottrell, 2015, d = 0.72,; Mendes Leal de Souza et al., 2016, d = 0.43; Sekir et al., 2016, d = 0.31) and peak isokinetic torque at 300°.s^{-1} (Sandberg et al., 2012, d = 0.21). Implementing a single set of 40-s of antagonist (pectoralis major) SS between sets of seated row exercises induced significant increases in total training volume and activation of agonist (latissimus dorsi) muscles (Miranda et al., 2015; Paz et al., 2013; 2016). However, they did not observe any changes in antagonist muscle activation (Miranda et al., 2015; Paz et al., 2013; 2016). Some studies employing longer durations of antagonist SS have reported performance enhancement. Cogley et al. (2021) investigated the effects of 8 sets of 30-s (240-s) SS on knee flexors on fast (300°.s^{-1}) and slow (60°.s^{-1}) knee extension for average power and found only a significant increase with the faster velocity. Sandberg et al. (2012) have suggested that the positive effects of antagonist SS might be velocity specific and primarily occur during faster movements.

Not all antagonist stretching protocols demonstrate performance enhancements. Using 40-s of SS divided into 2 sets of 20 s on knee flexors did not influence knee extension total training volume (Pessoa et al., 2023), while Jones and Humphrey (2018) reported no substantial improvements in VJ height, VJ power, and knee extensors peak power following 40-s of SS. Serefoglu et al. (2017) used the same SS intervention protocol (8 sets of 30-s) as Cogley et al. (2021) and did not find any significant increases in either slower (60°.s^{-1}) or faster (240°.s^{-1}) knee extension peak torque. One substantial difference with the Cogley et al. (2021) study is that Serefoglu et al. (2017) combined dynamic agonist stretching with static antagonist stretching. Also, one study utilizing 5 sets of 45-s (225-s) (Cè et al., 2021) SS of antagonist muscles (hamstrings and tibialis anterior) showed no substantial improvement in agonist MVC.

Studies incorporating 90-s (Sandberg et al., 2012), 120-s (Sekir et al., 2016), and 225 - 240-s (Cè et al., 2021; Serefoglu et al., 2017) of antagonist SS could not detect a significant decrease in agonist electromyography (EMG) amplitude. In contrast, 40-s SS of pectoralis major and shoulder adductors increased latissimus dorsi and biceps brachii EMG activity (Miranda et al., 2015; Paz et al., 2013; 2016). The studies that illustrated EMG increases showed performance improvements as well. Since only 40-s of antagonist SS on a specific muscle group has shown agonist EMG increases, these results might be muscle-, exercise-, or SS duration-specific.

In summary, the majority of studies examining the effects of antagonist SS on agonist performance reported significant performance enhancements regardless of their SS duration. However, these research studies focused solely on a specific duration of SS. To date, no study has explored and compared how varying durations of SS might influence the extent of performance enhancement or what the optimal duration of antagonist SS is for possibly improving agonist performance. Thus, the objective was to analyze the impact of varying durations (40-s (1 x 40-s), 80-s (2 x 40-s), and 120-s (3 x 40-s) of antagonist (dorsiflexors) SS on PF performance (ankle PF isometric and isokinetic peak torque, SDJ, and EMG). Based on prior research, 30-s (Elliott and Massey, 2020), 40-s, (Miranda et al., 2015; Paz et al., 2013; 2016), 90-s and 120-s (Miranda et al., 2015; Paz et al., 2016; Sandberg et al., 2012; Wakefield and Cottrell, 2015) and 240-s (Cogley et al. 2021) of antagonist SS can have a beneficial effect on agonist performance. Hence, it was hypothesized that while all antagonist (dorsiflexors) SS durations could improve PF (i.e., isometric and isokinetic peak torque) and jump (height, peak power, and reactive strength index) performance, an anticipated greater antagonist muscle force reduction and coactivation reduction would result in a greater positive performance impact with 120-s of antagonist SS.

Methods

Participants

An “a priori” statistical power analysis (software package, G * Power 3.1.9.7) was conducted based on effects of different antagonist SS durations on performance-related studies (Elliott and Massey, 2020; Sandberg et al., 2012) to achieve an alpha of 0.05, an effect size of 0.5, a statistical power of 0.8, and a correlation of 0.5 using the F-test family. The analysis indicated that between 16-30 participants should be sufficient to achieve adequate statistical power. It was possible to recruit 16 healthy active participants for this study (Table 1). Exclusion criteria included participants with a current injury to the quadriceps, hamstrings, or calf muscles and any injury in hip, ankle, or knee joints, medical issues that prevent performing a high-intensity exercise, or neurological conditions. Inclusion criteria included that, participants had reported to be healthy, between 18 - 40 years old, and engaged in strength training sessions 2 - 3 times per week on a regular basis.

Table 1. Participant characteristics (means ±SD).

Participants	Age (years)	Mass (kg)	Height (cm)
Male (n = 10)	30.5 ± 3.77	84.93 ± 14.48	176.96 ± 3.54
Female (n = 6)	27.67 ± 3.09	59.47 ± 5.5	161.33 ± 6.21

Prior to their lab visit, participants were given instructions to avoid intense activity (24 hours prior to participating), drinking alcohol, smoking, and using caffeine (12 hours prior to participating). Each participant completed the Physical Activity Readiness Questionnaire plus (PAR-Q+ 2022) and if they responded positively to any of the seven questions they were excluded from the study. Participants read and signed the informed consent form prior to testing and after a brief explanation of the study and the experiment's procedures. During their first visit to the lab, every participant became familiar with all measurements. The Interdisciplinary Committee on Ethics in Human Research (ICEHR #20241815-HK) gave its approval for this study.

Experimental design

The effects of different antagonist stretching durations on physical performance were investigated using a randomized crossover study design (Figure 1). The participants

became familiar with a basic orientation to the testing procedures and equipment during the initial familiarization session which was on a separate day from the testing sessions. They performed SDJ, slow and fast isokinetic as well as isometric PF peak torque tests pre- and post-SS. The participants then came to the lab for four distinct testing sessions with SS durations of 40-s, 80-s, 120-s, and control. Each session was randomized and separated by 48-72 hours. The SDJ was tested immediately after the antagonist stretch. In consideration of the time needed to set up the participant on the isokinetic device, this isokinetic testing was performed 3 minutes after the SDJ (5 minutes after the antagonist stretch).

Independent variables: Stretch interventions

To passively stretch the dorsiflexors, participants laid supine on a padded table with their feet hanging over the edge. An investigator moved both feet into plantar flexion by pulling on the distal segment of each foot and stretching the dorsiflexors until the maximum point of discomfort (POD). The stretching order of the dominant and non-dominant dorsiflexors was randomized. The thighs were strapped tightly to the training bed to minimize knee flexion. Among these sessions, three involved interventions (dorsiflexors (antagonist) SS) of varying durations (40-s, 80-s, and 120-s), and one served as a control (no stretching) session.

Dependent Variables: Measures

Electromyography (EMG)

Surface EMG was employed to document the muscle activity of the dominant leg (leg used to kick a soccer ball) soleus and tibialis anterior. Self-adhesive Cl/AgCl bipolar electrodes (MeditraceTM 130 ECG conductive adhesive electrodes, Syracuse, USA) were utilized in alignment with the muscle fibers and systematically positioned based on the guidelines outlined in "Surface Electromyography for the Non-Invasive Assessment of Muscles" (SENIAM) (Hermens et al., 1999). Hence, tibialis anterior (TA) electrodes were placed at 1/3 on the distance between the tip of the fibula and the tip of the medial malleolus, while soleus surface electrodes were positioned at 2/3 of the line between the medial condyle of the femur to the medial malleolus. Prior to placing the electrodes on the skin, the investigators prepared the area by shaving, abrading, and cleaning the skin with an isopropyl alcohol swab, allowing it to dry afterward (Hermens et al., 1999). The ground electrode was positioned on the lateral epicondyle of the femur, and all leads were secured to the skin to minimize potential movement artifacts in the surface EMG signal. Before commencing the experiment, a check was conducted to evaluate the inter-electrode noise, ensuring it remained below five kilo-ohms (5 kΩ). The EMG signals were amplified 1000x (CED 1902 Cambridge Electronic Design Ltd., Cambridge, UK) and filtered with a 3-pole Butterworth filter having band pass cut-off frequencies of 10-500 Hz. Analog signals were digitally converted at a sampling rate of 5 kHz using a CED 1401 interface (Cambridge Electronic Design Ltd., Cambridge, UK) and sampled at 2000 Hz. The intraclass correlation coefficient (ICC) reliability values for the pre-test soleus and TA EMG were 0.94 and 0.91, respectively.

Stiff Leg Drop Jump (SDJ)

To evaluate the SDJ performance of the participants, the Chronojump Boscosystem Contact Platform Kit (Chronojump-Boscosystem, Australia) was utilized. Previous studies supported the validity and reliability of this system (Pueo et al., 2020; Villalon et al., 2024). Participants were guided to stand on a step 30 cm above the ground with their hands on their hips (akimbo). They were directed to perform an SDJ where they were instructed to minimize knee and hip flexion while performing the jump to maximize the engagement of PF. After dropping onto the force platform (bilateral landing and jump), participants were requested to minimize their contact time (shortest time

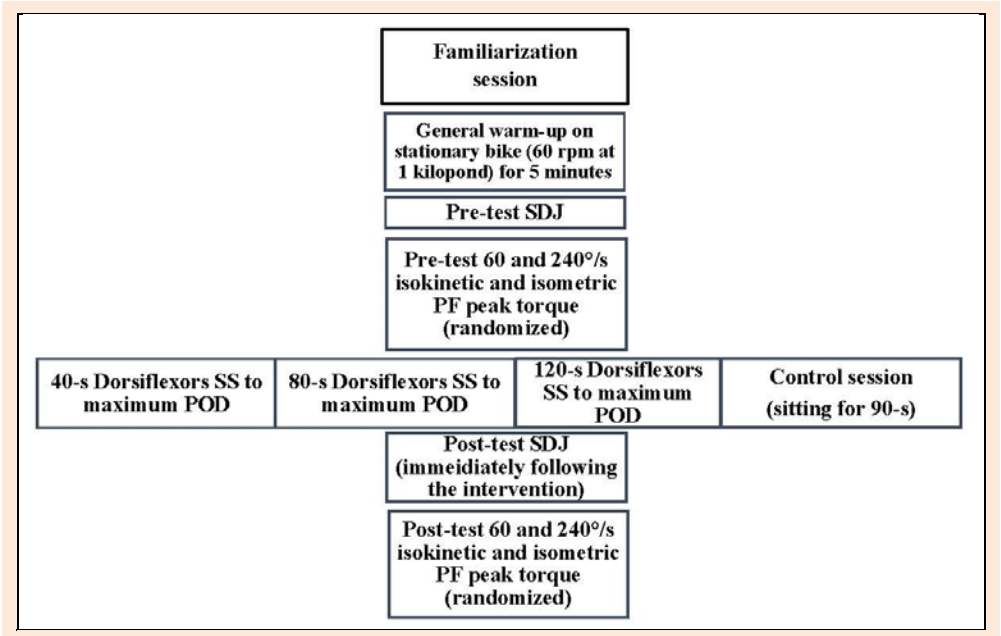

Figure 1. Experimental Design. The interventions were on four different days and the order was randomly assigned.
Acronyms: PF: plantar flexion, POD: maximum point of discomfort, SDJ: Stiff leg drop jump, SS: static stretching, TA: tibialis anterior.

possible) and immediately jumped as high as possible. The Chronojump Boscosystem software measured their jump height (cm), contact time (ms), jump power (Watts), and reactive strength index (RSI = jump height / contact time). Participants made three attempts, with a 1-minute rest interval between each and the highest jump out of the three jumps was reported. The post-test SDJ was tested immediately after the antagonist stretch intervention.

Ankle plantar flexion isokinetic and isometric peak torque

Participants were directed to sit on a Humac Norm Isokinetic Machine (Computer Sports Medicine Inc., Stoughton, MA, USA) chair. Upon being seated, they were secured to the chair using chest straps to minimize extraneous movements during the experiment. The chair back angle was set to 110°. The test was done for the dominant side leg. To hold the leg, participants' thigh was held and strapped on a thigh stabilizer pad. Participants' knee flexion angle was set to 150° (knee flexed at 30° from full extension [180°]). Then, their dominant foot was placed and strapped on a foot plate. The EMG leads were connected to the electrodes. Three different tests were performed by participants: a slow isokinetic (60 degrees/s), fast isokinetic (240 degrees/s), and isometric peak torque. The order of the tests was randomized in each session. A goniometer was employed to achieve an initial resting reference ankle angle of 90° for all participants. This ankle angle was considered the starting (reference) point from which the participants moved to the starting point at 10° of dorsiflexion with the isokinetic contraction ending at 40° of PF. Also, for the isometric test, the ankle angle was set to 10° of dorsiflexion based on manufacturer's instructions. During the familiarization session, participants could practice the isometric and isokinetic contractions (submaximal and maximal intensities) as many times as desired until they were comfortable with the procedure. During testing sessions and prior to pre-testing, participants performed three isometric and isokinetic contractions each at a subjective 50% of their maximal exertion. Preparation time for the participant on the isokinetic device necessitated that this test was performed 3 minutes after the SDJ (5 minutes after the antagonist stretch). Participants then did three maximum isokinetic plantar flexions at each speed, and the maximum peak torque among these was chosen. Additionally, participants did 2 - 3 isometric PF MVCs in 10° of dorsiflexion. The peak torque (Nm) value obtained during the first MVC was recorded. If the value for the second MVC was 5% greater than the first, a third MVC was conducted to ensure that the participant reached their maximum torque production. The torque signal from the isokinetic dynamometer was delivered to the BioPac AcqKnowledge software program to synchronize torque and EMG signals.

Statistical analysis

Statistical analyses were calculated using SPSS software (Version 28.0, SPSS, Inc, Chicago, IL). This study employed a repeated measure, within-subjects, crossover design. Kolmogorov–Smirnov tests of normality were conducted for all dependent variables. Significance was defined as $p \leq 0.05$. The Shapiro-Wilk test indicated all data were normally distributed. Mauchly's test indicated that the assumption of sphericity was met for all measures (Tables 2 - 5). If the assumption of sphericity was violated, the Greenhouse–Geiser correction was employed. Since every subject underwent four sessions/conditions (40-s, 80-s, 120-s, and control) and during each session two measurements were performed (pre- and post-SS), a 4x2 repeated measures ANOVA was employed. Bonferroni post-hoc tests were conducted to detect significant main effect differences between conditions (SS durations and control) whereas, for significant interactions, Bonferroni post-hoc t-tests corrected for multiple comparisons (α-value divided by the number of analyses on the dependent variable) were conducted to determine differences between values. Partial Eta-squared (η_p^2) values are reported for main effects and overall interactions representing small ($0.01 \leq \eta_p^2 < 0.06$), medium ($0.06 \leq \eta_p^2 < 0.14$) and large ($\eta_p^2 \geq 0.14$) magnitudes of change (Cohen, 2013). Cohen's d effect sizes are reported for the specific post-hoc interactions with $d < 0.2$: trivial, 0.2 - <0.5: small, 0.5 - <0.8: moderate, ≥0.8: large magnitude difference (Cohen, 2013). Mean and standard deviation (mean ± SD) data are illustrated for all measures as supplementary files on the journal web site and anonymized individual data sets can be forwarded to interested individuals upon request to the corresponding author.

Results

The Shapiro-Wilk test indicated all data were normally distributed.

Isometric and isokinetic peak torque

There were no statistically significant interaction of condition*time or main effect of condition for any condition. Main effects for time for the slow (6.6%, d = 0.24) and fast isokinetic (5.9%, d = 0.24) peak torque indicated significant, small magnitude torque decreases from pre- (106.5 ± 28.7 Nm) to post-test (99.4 ± 29.7 Nm) for slow isokinetic, and from pre- (58.3 ± 13.5 Nm) to post-test (54.9 ± 14.1 Nm) for fast isokinetic (Table 2a and Table 2b).

Total work

There was no statistically significant interaction of condition*time, main effect of condition or time (Table 3a and Table 3b) for any condition with the exception of a main effect for time for the fast isokinetic total work. Fast isokinetic total work displayed a significant ($p = 0.025$, $\eta^2 = 0.294$), small magnitude (5.1%, d = 0.20) decrease from pre- (83.3 ± 21.8 J) to post-test (79.0 ± 21.6 J). A trivial magnitude decrease (1.9%, d = 0.07) in total work was evident with the slow isokinetic contraction, although it did not reach significance ($p = 0.06$).

Stiff Leg Drop Jump (SDJ)

There was no statistically significant interaction of condition*time. A main effect for condition revealed that SDJ demonstrated that both 40-s (21.05 ± 4.2 cm, 5.6%, d = 0.30, $p = 0.017$) and 80-s (21.4 ± 4.1 cm, 4.0%, d = 0.22, $p = 0.002$) of antagonist stretching produced a significant, small magnitude reduction in jump height compared to the control (22.3 ± 4.0 cm) session. There was no significant

change with the 120-s condition. There was a main effect for time for all the measures (Table 4a and Table 4b) significant decreases from pre- to post-test (SDJ height: $p = 0.02$, $\eta^2 = 0.31$, 2.7%, $d = 0.15$, RSI: $p < 0.001$, $\eta^2 = 0.36$, 5.9%, $d = 0.23$, peak power: $p = 0.002$, $\eta^2 = 0.49$, 4.4%, $d = 0.22$) ranged from trivial to small magnitude changes.

Table 2a. Isometric, slow and fast isokinetic peak torque (Nm) values (means ± SD).

	40-s		80-s		120-s		Control	
	pre	post	pre	post	pre	post	pre	post
ISOM PT	171.5 ± 43.9	175.6 ± 49.9	188.9 ± 48.4	183.7 ± 47.8	187.1 ± 42.9	188.9 ± 43.7	183.1 ± 53.3	179.1 ± 50.6
ISOK PT (60°/s)	97.5 ± 31.1	93.9 ± 31.8	102.6 ± 28.8	103.2 ± 30.3	100.6 ± 26.2	103.7 ± 29.2	102.9 ± 29.9	97.3 ± 26.5
ISOK PT (240°/s)	57.0 ± 14.4	53.2 ± 15.9	60.7 ± 14.5	55.1 ± 14.6	57.7 ± 14.2	56.1 ± 11.8	58.2 ± 11.8	55.6 ± 14.3

ISOM: isometric; ISOK: isokinetic; PT: peak torques (Nm).

Table 2b. Illustrates Mauchley's test of sphericity and significance values for isometric, as well as slow and fast isokinetic peak torque (Nm). Bolded boxes highlight significant differences.

	Mauchley's Sphericity assumption met		Significance		
	Duration *time	Duration	Duration *time	Duration Main Effect	Time Main Effect
ISOM PT	($\chi^2(5) = 7.343$, $p = 0.19$)	($\chi^2(5) = 0.630$, $p = 0.98$),	($F(3, 45) = 1.905$, $p = 0.14$, $\eta^2 = 0.11$)	($F(3, 45) = 1.219$, $p = 0.314$, $\eta^2 = 0.07$)	($F(1, 15) = 0.350$, $p = 0.56$, $\eta^2 = 0.02$).
ISOK PT (60°/s)	**($\chi^2(5) = 17.178$, $p = 0.004$)**	($\chi^2(5) = 4.071$, $p = 0.54$),	$F(1.784, 26.753) = 2.040$, $p = 0.15$, $\eta^2 = 0.12$	$F(3, 45) = 0.824$, $p = 0.48$, $\eta^2 = 0.05$	**$F(1, 15) = 4.478$, $p = 0.05$, $\eta^2 = 0.23$**
ISOK PT (240°/s)	**$\chi^2(5) = 23.207$, $p < 0.0001$**	$\chi^2(5) = 9.459$, $p = 0.093$	$F(1.753, 26.288) = 0.953$, $p = 0.38$, $\eta^2 = 0.06$	$F(3, 45) = 0.402$, $p = 0.75$, $\eta^2 = 0.02$	**$F(1, 15) = 32.414$, $p < 0.0001$, $\eta^2 = 0.68$**

ISOM: isometric; ISOK: isokinetic; PT: peak torques (Nm).

Table 3a. Slow and fast isokinetic total work (Joules) values (means ± SD).

	40-s		80-s		120-s		Control	
	pre	post	pre	post	pre	post	pre	post
ISOK TW (60°/s)	159.7 ± 51.3	157.0 ± 54.3	161.3 ± 41.3	164.6 ± 46.9	162.5 ± 40.3	156.1 ± 38.9	165.8 ± 34.2	159.1 ± 42.6
ISOK TW (240°/s)	81.3 ± 23.2	75.2 ± 23.2	87.4 ± 22.7	79.7 ± 22.4	83.7 ± 29.6	75.8 ± 15.0	80.8 ± 13.7	80.5 ± 17.4

ISOK: isokinetic; TW: total work

Table 3b. Illustrates Mauchley's test of sphericity and significance values for slow and fast isokinetic total work (Joules). Bolded boxes highlight significant differences.

	Mauchley's Sphericity assumption met		Significance		
	Duration *time	Duration	Duration *time	Duration Main Effect	Time Main Effect
ISOK TW (60°/s)	**$\chi^2(5) = 10.957$, $p = 0.05$**	$\chi^2(5) = 2.395$, $p = 0.79$	($F(3, 45) = 1.159$, $p = 0.33$, $\eta^2 = 0.07$)	($F(3, 45) = 0.156$, $p = 0.92$, $\eta^2 = 0.01$)	($F(1, 15) = 3.905$, $p = 0.06$, $\eta^2 = 0.21$
ISOK TW (240°/s)	$\chi^2(5) = 1.060$, $p = 0.95$	$\chi^2(5) = 2.112$, $p = 0.65$	$F(3, 45) = 1.400$, $p = 0.255$, $\eta^2 = 0.085$	$F(3, 45) = 0.708$, $p = 0.55$, $\eta^2 = 0.04$	**$F(1, 15) = 6.242$, $p = 0.02$, $\eta^2 = 0.29$**

ISOK: isokinetic; TW: total work

Stiff Leg Drop Jump (SDJ)

There was no statistically significant interaction of condition*time. A main effect for condition revealed that SDJ demonstrated that both 40-s (21.05 ± 4.2 cm, 5.6%, $d = 0.30$, $p = 0.017$) and 80-s (21.4 ± 4.1 cm, 4.0%, $d = 0.22$, $p = 0.002$) of antagonist stretching produced a significant, small magnitude reduction in jump height compared to the control (22.3 ± 4.0 cm) session. There was no significant change with the 120-s condition. There was a main effect for time for all the measures (Table 4a and Table 4b) significant decreases from pre- to post-test (SDJ height: $p = 0.02$, $\eta^2 = 0.31$, 2.7%, $d = 0.15$, RSI: $p < 0.001$, $\eta^2 = 0.36$, 5.9%, $d = 0.23$, peak power: $p = 0.002$, $\eta^2 = 0.49$, 4.4%, $d = 0.22$) ranged from trivial to small magnitude changes.

Electromyography (EMG)

Statistically significant interactions of condition*time except were only evident for soleus isometric and slow isokinetic EMG (Table 5). Soleus isometric EMG with 120-s of SS was significantly (moderate magnitudes) lower with post-test than pre-test ($p = 0.002$, 13.6%, $d = 0.73$) while control post-test was significantly lower than control pre-test ($p = 0.004$, 8.5%, $d = 0.54$). Similarly, soleus EMG with 120-s of SS during slow isokinetic contractions exhibited significant, large magnitude lower activation at post- versus pre-test ($p = 0.002$, 12.3%, $d = 0.91$). Similarly, with 80-s of antagonist SS, soleus EMG post-test demonstrated large magnitude significantly lower activity than pre-test ($p = 0.02$, 6.6%, $d = 0.75$). With the control condition, post-test soleus EMG was also lower than pre-test ($p = 0.004$, 10.7%, $d = 0.77$) (Table 6) (Figure 2 and Figure 3).

The main effect of condition was not significant for any condition with the exception for soleus slow isokinetic EMG where the duration of 120-s showed a signify-cant, large magnitude higher activation than 80-s ($p = 0.030$, 11.4%, $d = 1.12$) (Table 5 and Table 6). The main effect of time was significant with small to moderate magnitude decreases from pre- to post-test for all the conditions (Table 5, Table 6 and Table 7).

Table 4a. **Stiff leg drop jump (SDJ) height (cm), contact time (CT, ms), reactive strength index (RSI, m/sec), and peak power (PP, watt) values (means ±SD).**

	40-s		80-s		120-s		Control	
	pre-	post-	pre-	post-	pre-	post-	pre-	post-
Height	21.2 ± 3.9	20.9 ± 4.5	21.4 ± 3.7	21.1 ± 4.4	21.5 ± 3.6	20.9 ± 4.1	22.8 ± 3.9	21.9 ± 4.1
CT	265.2 ± 48.7	258.9 ± 55.5	257.7 ± 44.4	263.3 ± 54.8	259.1 ± 43.4	278.5 ± 54.5	259.4 ± 44.3	267.9 ± 49.9
RSI	0.8 ± 0.22	0.81 ± 0.20	0.83 ± 0.21	0.80 ± 0.21	0.83 ± 0.20	0.75 ± 0.21	0.88 ± 0.24	0.82 ± 0.28
PP	26.8 ± 5.3	25.7 ± 4.7	26.6 ± 5.0	25.5 ± 5.1	26.4 ± 4.4	24.9 ± 5.1	27.7 ± 5.4	26.3 ± 6.3

RSI: reactive strength index (RSI=HT(meters)/CT(seconds).

Table 4b. **Illustrates Mauchley's test of sphericity and significance values for Stiff leg drop jump (SDJ) height (cm), reactive strength index (RSI, m/sec), and peak power (PP, watt). Bolded boxes highlight significant differences.**

	Mauchley's Sphericity assumption met		Significance		
	Duration *time	Duration	Duration *time	Duration Main Effect	Time Main Effect
Height	$\chi^2(5) = 7.22$, $p = 0.21$	$\chi^2(5) = 16.63$, $p = 0.005$	$F(3, 45) = 1.02$, $p = 0.39$, $\eta^2 = 0.06$	**$F(1.8, 27.7) = 4.95$, $p = 0.01$, $\eta^2 = 0.24$**	**$F(1, 15) = 6.96$, $p = 0.02$, $\eta^2 = 0.317$**
RSI	$\chi^2(5) = 5.43$, $p = 0.36$	$\chi^2(5) = 7.31$, $p = 0.19$	$F(3, 45) = 0.87$, $p = 0.45$, $\eta^2 = 0.05$	$F(3, 45) = 2.59$, $p = 0.06$, $\eta^2 = 0.14$	**$F(1, 15) = 19.66$, $p < 0.001$, $\eta^2 = 0.56$**
Peak Power	$\chi^2(5) = 9.43$, $p = 0.09$	$\chi^2(5) = 9.28$, $p = 0.09$	$F(3, 45) = 0.21$, $p = 0.89$, $\eta^2 = 0.01$	$F(3, 45) = 2.30$, $p = 0.09$, $\eta^2 = 0.13$	**$F(1, 15) = 14.51$, $p = 0.002$, $\eta^2 = 0.49$**

RSI: reactive strength index (RSI=HT(meters)/CT(seconds).

Table 5. **illustrates Mauchley's test of sphericity and significance values for EMG. Bolded boxes highlight significant differences.**

	Mauchley's Sphericity assumption met		Significance		
	Duration *time	Duration	Duration *time	Duration Main Effect	Time Main Effect
Soleus ISOM	$\chi^2(5) = 4.72$, $p = 0.45$	$\chi^2(5) = 1.08$, $p = 0.95$	**$F(3, 45) = 6.12$, $p = 0.001$, $\eta^2 = 0.29$**	$(F(3, 45) = 1.657$, $p = 0.19$, $\eta^2 = 0.09$	**$F(1, 15) = 13.755$, $p = 0.002$, $\eta^2 = 0.47$**
Soleus ISOK (60°/s)	$\chi^2(5) = 9.89$, $p = 0.08$	$\chi^2(5) = 1.41$, $p = 0.92$	**$F(3, 45) = 4.920$, $p = 0.005$, $\eta^2 = 0.24$**	**$F(3, 45) = 4.071$, $p = 0.01$, $\eta^2 = 0.21$**	**$F(1, 15) = 23.878$, $p < 0.001$, $\eta^2 = 0.61$**
Soleus ISOK (240°/s)	$\chi^2(5) = 8.80$, $p = 0.12$	$\chi^2(5) = 10.947$, $p = 0.053$	$F(3, 45) = 1.857$, $p = 0.15$, $\eta^2 = 0.11$	$F(3, 45) = 0.234$, $p = 0.87$, $\eta^2 = 0.01$	**$F(1, 15) = 13.915$, $p = 0.002$, $\eta^2 = 0.48$**
Tibialis Anterior ISOM	$\chi^2(5) = 3.49$, $p = 0.62$	$\chi^2(5) = 1.992$, $p = 0.85$	$F(3, 45) = 1.992$, $p = 0.13$, $\eta^2 = 0.11$	$F(3, 45) = 2.539$, $p = 0.06$, $\eta^2 = 0.14$	**$F(1, 15) = 5.710$, $p = 0.03$, $\eta^2 = 0.17$**
Tibialis Anterior Soleus ISOK (60°/s)	$\chi^2(5) = 17.09$, $p = 0.004$	$\chi^2(5) = 3.46$, $p = 0.63$	$F(1.6, 25.1) = 2.155$, $p = 0.14$, $\eta^2 = 0.12$	$F(3, 45) = 1.816$, $p = 0.15$, $\eta^2 = 0.11$	**$F(1, 15) = 8.454$, $p = 0.01$, $\eta^2 = 0.36$**
Tibialis Anterior ISOK (240°/s)	$\chi^2(5) = 7.47$, $p = 0.18$	$\chi^2(5) = 4.28$, $p = 0.51$	$F(3, 45) = 1.029$, $p = 0.38$, $\eta^2 = 0.06$	$F(3, 45) = 1.804$, $p = 0.16$, $\eta^2 = 0.10$	**$F(1, 15) = 9.435$, $p = 0.008$, $\eta^2 = 0.38$**

ISOM: isometric; ISOK: isokinetic.

Table 6. **Mean and standard deviation (mean ±SD) data illustrated for all EMG measures (mV).**

		Soleus ISOM	Soleus ISOK (60°/s)	Soleus ISOK (240°/s)	Tibialis Anterior ISOM	Tibialis Anterior ISOK (60°/s)	Tibialis Anterior ISOK (240°/s)
40-s	Pre-	0.223 ± 0.05	0.222 ± 0.05	0.246 ± 0.06	0.074 ± 0.03	0.084 ± 0.02	0.092 ± 0.03
	Post-	0.213 ± 0.04	0.224 ± 0.04	0.227 ± 0.03	0.072 ± 0.02	0.082 ± 0.03	0.088 ± 0.03
80-s	Pre-	0.213 ± 0.04	0.224 ± 0.02	0.235 ± 0.03	0.078 ± 0.02	0.094 ± 0.03	0.106 ± 0.03
	Post-	0.211 ± 0.03	0.209 ± 0.02	0.236 ± 0.04	0.077 ± 0.02	0.087 ± 0.03	0.095 ± 0.03
120-s	Pre-	0.242 ± 0.05	0.260 ± 0.05	0.249 ± 0.04	0.080 ± 0.02	0.100 ± 0.02	0.103 ± 0.03
	Post-	0.209 ± 0.04	0.228 ± 0.02	0.235 ± 0.03	0.073 ± 0.02	0.090 ± 0.02	0.095 ± 0.02
Control	Pre-	0.221 ± 0.04	0.252 ± 0.04	0.248 ± 0.05	0.069 ± 0.01	0.086 ± 0.02	0.093 ± 0.03
	Post-	0.202 ± 0.03	0.225 ± 0.03	0.236 ± 0.05	0.061 ± 0.01	0.077 ± 0.02	0.085 ± 0.02

ISOM: isometric; ISOK: isokinetic.

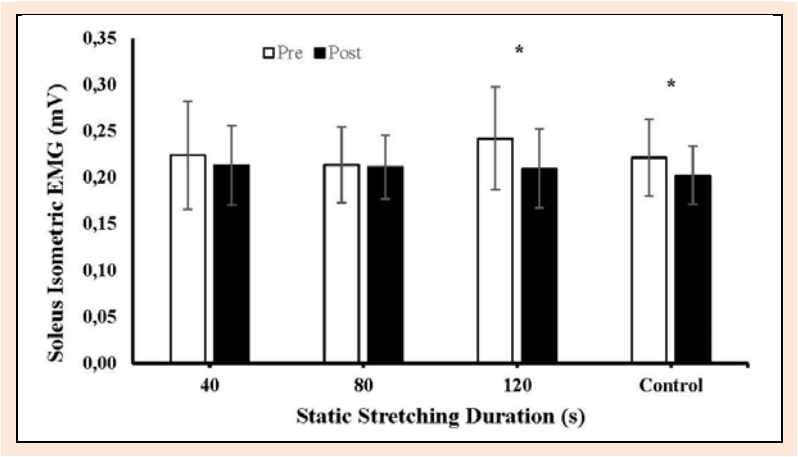

Figure 2. Illustrates the interaction of conditions (antagonist stretching for 40-s, 80-s, 120-s and control) and time (pre- and post-test) for soleus isometric EMG. * indicates significance.

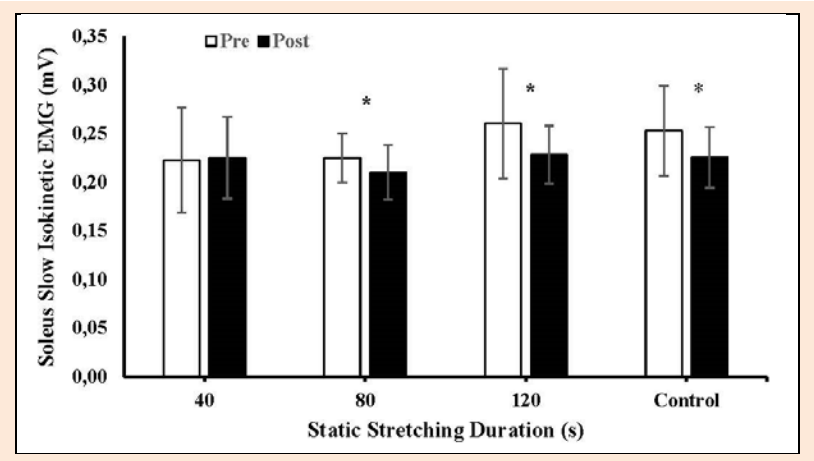

Figure 3. Illustrates the interaction of conditions (antagonist stretching for 40-s, 80-s, 120-s and control) and time (pre- and post-test) for soleus slow isokinetic EMG. * indicates significance.

Table 7. Illustrates the significance and effect sizes for the main effect of time for EMG.

	Significance	Effect Size
Soleus Isometric	**0.002**	**0.478**
Soleus Slow Isokinetic	**0.001**	**0.614**
Soleus Fast Isokinetic	**0.002**	**0.481**
Tibialis Anterior Isometric	**0.030**	**0.276**
Tibialis Anterior Slow Isokinetic	**0.011**	**0.360**
Tibialis Anterior Fast Isokinetic	**0.008**	**0.386**

Discussion

The major findings of this study were a) there were no interaction effects of specific antagonist stretching durations (40-s, 80-s, 120-s) on pre- to post-intervention PF isometric peak torque, slow or fast isokinetic peak torque, total work, or SDJ height, RSI, and peak power. Without a significant interaction, the main effect for conditions showing that SDJ jump heights were lower with 40-s and 80-s of antagonist stretching versus control with no significant change with 120-s did not provide robust evidence for antagonist-stretching-induced impairments. The main effect for time (all conditions combined including the control condition) with an overall decrease in fast (240^0/s) and slow (60^0/s) isokinetic peak torque, total work, SDJ measures, and soleus EMG decreases with the control condition suggests a possibility that testing influenced the deficits.

In accordance with the present findings, Serefoglu et al. (2017) observed that performing 4 sets of 30-s (120-s) SS for knee flexors did not significantly affect isokinetic peak torque or EMG for either slow (60^0/s) or fast (240^0/s) knee extensions. Similarly, Cogley et al. (2021) conducted a study with 8 sets of 30-s of SS (240s) and found no changes in either peak torque or total work, although they did report a significant increase in average power for fast isokinetic (300^0/s) contractions. Similar to the 80-s of SS in the present study, Sandberg et al. (2012), could not find any significant changes in fast isokinetic peak torque for knee extensors after stretching knee flexors for 90-s. To the best of the authors' knowledge, this is the first study to investigate the isometric peak torque as well as isokinetic peak torque on this topic. Only one study examined the isometric performance of the dorsiflexors MVC and showed no significant difference after stretching PF for 225-s (Ce et al. 2020). Jones and Humphrey (2018) explored the impact of stretching hip flexors and dorsiflexors for 90-s on VJ height and power and did not find significant differences. Our study also found no significant changes in SDJ performance (height, power, and RSI) across all durations, consistent with the findings of Jones and Humphrey (2018).

Our current study showed significant reductions in soleus EMG after SS the dorsiflexors for 80-s and 120-s in the slow isokinetic protocol and 120-s SS in the isometric protocol, however, we were not able to show any significant differences in either soleus or tibialis anterior EMG after all other SS durations and testing protocols. Two studies examined the antagonist muscles EMG while doing an isometric protocol and are in agreement with our findings. Sandberg et al. (2012) demonstrated that 90-s of knee flexors SS did not significantly increase knee extensors EMG activity. Similarly, another study by Cè et al. (2021) reported that 240-s of knee flexors SS failed to produce significant changes in the knee extensors EMG activity. These studies were not able to show any significant changes in the stretched muscle either. Only one study examined the EMG while testing isokinetic peak torque after 240-s of SS (8x30-s) and did not show any significant changes in either hamstrings after stretching quadriceps or quadriceps after stretching the hamstrings. (Serefoglu et al., 2017). Finally, Sekir et al. (2016) found that 120-s of dorsiflexors and hip flexors SS did not affect the plantar flexors and hip extensors EMG activity while doing a VJ test.

Some studies do not support the lack of antagonist stretching-induced changes in performance or EMG activity found in the present study. For example, both Sandberg et al. (2012) and Wakefield and Cottrell (2015) showed that 90-s (3x30-s) SS of knee flexors, hip flexors, and dorsiflexors that are all antagonist muscles while doing a VJ resulted in a significant improvement in VJ height and power and also knee extensions fast isokinetic peak torque (300^0/s). Also, Cogley et al. (2021) found similar positive results for knee extensions fast isokinetic peak torque after 240-s (8x30-s) of stretching the antagonist hamstrings. In addition, Sekir et al. (2016) showed that 120-s of antagonist (hip flexors, knee flexors, and dorsiflexors) SS can improve the VJ height substantially although there was no change in EMG. Three studies applied 40-s of pectoralis major SS and found significant improvement in seated row training volume and substantial increase in latissimus dorsi and biceps brachii EMG but no changes in stretched muscles' EMG (Miranda et al., 2015; Paz et al., 2016; 2013). The reasons these studies do not support our results may be attributed to a number of factors. First of all, the antagonist effects of SS might be muscle or muscle size specific. Some studies stretched knee flexors (Sandberg et al., 2012; Wakefield and Cottrell, 2015), while others stretched the pectoralis major (Miranda et al., 2015; Paz et al., 2013; 2016). These muscles are larger (greater volume) than the dorsiflexors, which was stretched in this study.

Whereas it was hypothesized that antagonist (dorsiflexors) SS could improve PF performance, with the greatest effects with 120-s of antagonist stretching, there was not convincing evidence. Since an increased extent or inappropriate timing of co-contractile activity is often reported to provide a "braking effect" (Dal Maso et al., 2012; Sandberg et al., 2012) hindering the agonist from achieving its maximum force or power (Baratta et al., 1988; Draganich et al., 1989), prolonged stretching of the antagonist was postulated to decrease co-contractile neuromuscular activation (Fowles et al., 2000) and reduce musculotendinous unit compliance (Fowles et al., 2000; Kallerud and Gleeson, 2013) attenuating the antagonist counteracting force. However, the lack of significant changes may be attributed to the size and strength difference between the agonist and antagonist. Dorsiflexors are not as large and strong as plantar flexors suggesting it may not be able to affect the performance as significantly and hence this force and size imbalance might impede antagonist influences compared to larger muscle groups. Furthermore, the stretching method employed in the current study may not have been sufficient to elicit significant changes, as inducing only PF to stretch the tibialis anterior, which runs diagonally across the tibia from the lateral to medial side diagonally, presents certain challenges. Another factor that might explain the difference is SS duration and intensity. However, based on the studies mentioned above, SS duration ranged from 40-s to 240-s. Also, only three studies mentioned their SS intensity and all of them explained it as a mild discomfort, however, the precise definition of mild discomfort was not clarified (Sandberg et al., 2012; Wakefield and Cottrell, 2015; Miranda et al., 2015). It should be noted in our current study the SS was performed at the maximum point of discomfort.

There are a few studies that examined the effects of 90-s of antagonist SS on VJ height and all found significant increases in VJ height after the SS protocol (Sandberg et al., 2012; Wakefield and Cottrell, 2015; Caldwell et al. 2019). The lower SDJ height results with 40-s and 80-s conditions were identified as main effects for conditions, thus combining both pre- and post-test data. Since the present findings include both pre- and post-test results, there is no convincing evidence for a significant or substantial SDJ height decrements.

Limitations

Whereas one of the goals was to compare differences between male and female groups there were challenges in recruiting a sufficient number of female participants that prevented this objective from being achieved. However, it is unlikely that the inclusion of females would have significantly affected the results as this was a repeated measures study and thus within individual differences over time were considered. Secondly, while women tend to possess absolutely greater range of motion than men, their relative increase in response to a single session of stretching or stretch training is similar to men (Konrad et al. 2024; Behm et al. 2023). Also, there was a limitation while doing SDJ testing. Although we asked all the participants to minimize bending their hip and knee joints to focus more on the PF muscles, it was inevitable that there may have been some minor engagement of knee extensors and hip extensors while jumping. An analysis of the gastrocnemius activation may also have been beneficial, however, the soleus is more predominant in a flexed knee position. Future studies can also look at the neural activity of the gastrocnemius and compare the results with the soleus. Finally, although our EMG inter-session reliability was excellent, we are aware that normalization of the signal over multiple days might have provided even greater reliability.

Conclusion

This study explored the effects of antagonist (dorsiflexors) stretching durations on various PF performance measures. The primary outcome indicated that different durations of antagonist SS (40-s, 80-s, 120-s) did not significantly influence pre- to post-intervention isometric peak torque, isokinetic peak torque (both slow and fast), total work, or measures of SDJ, including height, RSI, and peak power. However, testing effects may have been evident, since with all conditions combined (including control), there was a general decline in fast and slow isokinetic peak torque, total work, and all SDJ measures.

A significant reduction in soleus EMG activity was observed during isometric and slow isokinetic protocols following 80-s and 120-s of SS, further indicating testing effects. The findings align with previous research that showed no significant changes in peak torque or EMG following various stretching protocols. While some studies reported improvements in performance measures after antagonist stretching, these discrepancies may be due to differences in co-contractile muscle size, strength, and stretching protocols.

Practical implications

The findings of this study suggest that incorporating antagonist (dorsiflexors) stretching into pre-exercise routines, especially for durations of 40-s, 80-s, or 120-s, may not significantly enhance nor impair PF isometric or isokinetic performance, or jump-related metrics such as SDJ height, RSI, or peak power. Additionally, the observed decreases in soleus EMG activity indicate that testing effects should be taken into account.

Acknowledgments

There was no conflict of interest. The present study complies with the current laws of the country in which it was performed and was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of Memorial University of Newfoundland (protocol code 20241319-HK. Date of approval: January 18, 2024). The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author upon request. This study was funded by a grant for Dr. Behm from the Natural Science and Engineering Research Council (NSERC) of Canada (RGPIN-2023-05861). Informed consent was obtained from all subjects involved in the study. The authors declare no conflicts of interest.

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Key points

- Different durations of antagonist (dorsiflexors) SS (40-s, 80-s, 120-s) did not significantly influence pre- to post-intervention isometric peak torque, isokinetic peak torque (both slow and fast), total work, or measures of SDJ, including height, RSI, and peak power.
- With all stretch durations and control conditions combined, there was a general decline in fast and slow isokinetic peak torque, total work, and all SDJ measures, suggesting the presence of testing effects.
- Significant reductions in soleus EMG activity during isometric and slow isokinetic protocols following 80-s and 120-s of SS, also suggest testing effects.

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