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The Effects of High-Intensity, Low-Duration and Low-Intensity, High-Duration Hamstrings Static Stretching on Contralateral Limb Performance

Running Title: Crossover Effects of High and Low Intensity Stretching

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Abstract: Introduction: Increases in contralateral range of motion (ROM) have been shown following acute high-intensity and high-duration static stretching (SS) with no significant change in contralateral force, power, and muscle activation. There are currently no studies comparing the effects of a high-intensity, low-duration (HILD) or low-intensity, high-duration (LIHD) SS on contralateral performance. **Purpose:** The aim of this study was to examine how HILD and LIHD SS of the dominant leg hamstrings influence contralateral limb performance. **Methods:** Sixteen trained participants (8 females, 8 males) completed three SS interventions of the dominant leg hamstrings; 1) HILD (6x10s at maximal point of discomfort (POD)), 2) LIHD (6x30s at initial POD), and 3) control. Dominant and non-dominant ROM, maximal voluntary isometric contraction (MVIC) forces, muscle activation (electromyography (EMG)), unilateral CMJ and DJ heights were recorded pre-test and 1-minute post-test. **Results:** There were no significant contralateral ROM or performance changes. Following the HILD condition, the post-test ROM for the stretched leg (110.6±12.6^0) exceeded the pre-test (106.0±9.0^0) by 4.2% (p=0.008). Similarly, with LIHD, the stretched leg post-test (112.2±16.5^0) also exceeded (p=0.06) the pre-test ROM (109.3±16.2^0) by 2.6%. There were large magnitude impairments, evidenced by main effects for testing time for force, instantaneous strength, and associated EMG. A significant ROM interaction (p=0.02) showed that with LIHD, the stretched leg significantly (p=0.05) exceeded the contralateral leg by 13.4% post-test. **Conclusion:** The results showing no significant increase in contralateral ROM with either HILD or LIHD SS suggesting the interventions may not have been effective in promoting crossover effects.

Keywords: range of motion; maximal voluntary isometric contraction; muscle activation; stretch tolerance; flexibility

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Introduction

Static stretching (SS) is the most prevalent method of stretching with fitness, sport, and rehabilitation (Nakamaura et al., 2021), with an individual holding a stationary stretching position placing tension on the muscle tendon unit (MTU) often to the maximum range of motion (ROM) or point of discomfort (POD). The optimal SS prescription regarding the dose-response relationship between SS duration and intensity on range of motion (ROM) and maximal muscle performance has been heavily debated for many years. In the current literature, it is often suggested that longer duration SS (>60 s per muscle group) is more likely to cause muscle performance impairments (i.e., force, power, vertical jump height) than shorter duration SS (<60 s per muscle group) (Behm & Chaouachi 2011; Behm et al. 2016a, 2021d, Kay & Blazevich 2012; Kay & Blazevich 2008; Reid et al.

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2018). In some studies, higher intensity SS has also been suggested to result in greater ROM increases than lower intensity SS, although low-intensity SS still demonstrates increases in ROM (Nakamura et al. 2021; Kataura et al. 2017). However, recent meta-analytical reviews provide evidence that SS intensity may not moderate the effects of muscle strength, power (Arntz et al. 2023), or ROM (Behm et al. 2016a; Konrad et al. 2023) and there is no association between high duration SS and increased ROM (Konrad et al. 2023). Thus, the recommended SS prescription remains unclear.

Several original studies (Caldwell et al. 2019; Chaouachi et al. 2017; Behm et al. 2019; Marchetti et al. 2017; Anvar et al. 2023) have reported an increase in crossover (non-local or contralateral limb) ROM following an acute bout of SS. A meta-analysis by Behm et al. (2021a) reported that 240-s of SS exhibited large magnitude increases in non-local ROM compared to moderate magnitude improvements with shorter (<120-s) SS durations. As the non-local or contralateral limb is not physically stretched in these scenarios, it is postulated that the increase in ROM cannot be attributed to morphological mechanisms such as increased MTU compliance (Behm et al. 2016b; 2019; Chaouachi et al. 2017; Hadjizadeh Anvar et al. 2023). Increased stretch tolerance is a commonly suggested mechanism underlying an increase in ROM of the stretched limb (Behm et al. 2016a; 2021d; Magnusson et al. 1996) as well as with non-stretched contralateral and non-local muscles and joints (Hadjizazdeh Anvar et al. 2023; Chaouachi et al. 2017; Behm et al. 2016b; 2019; 2021a; Marchetti et al. 2017; Wicke et al. 2014).

Several studies exhibiting these non-local ROM changes have not reported a decrease in contralateral limb force, power (Chaouachi et al. 2017), or muscle activation (Behm et al. 2019; Hadjizadeh Anvar et al. 2023). For example, Hadjizadeh Anvar et al. (2023) showed significant increases in contralateral ROM following 6x45-s SS of the dominant leg plantar flexors to the POD with no significant decrease in contralateral force. Similarly, Behm et al. (2019) showed significant increases in stretched and non-stretched contralateral leg ROM following 8x30s SS of the dominant leg quadriceps and hamstrings with no significant changes in MVC or muscle activation, further emphasizing an increase in stretch tolerance as a mechanism for this increase in ROM. Global pain/stretch modulatory systems such as diffuse noxious inhibitory control (DNIC) and gate control theory are suggested to contribute to an increase in stretch tolerance (Behm et al. 2016b; 2021a;c; Hadjizadeh Anvar et al. 2023) causing a suppressed transmission or analgesic effect on pain throughout the body and therefore, an increased ability to withstand discomfort and push through a greater ROM ((Behm et al. 2016b; 2021a;c; Hadjizadeh Anvar et al. 2023). Several studies examining the effects of acute SS on contralateral limb performance typically administer high-intensity (to the maximum POD), high-duration (> 60s) SS (Chaouachi et al. 2017; Behm et al. 2019; Hadjizadeh Anvar et al. 2023). There are no studies investigating the effects of high-intensity, low-duration (HILD) or low-intensity, high-duration (LIHD) SS on contralateral limb performance.

Thus, the purpose of the present study was to examine the effects of HILD and LIHD SS of the dominant leg hamstrings on contralateral limb performance. It was hypothesized that greater contralateral limb ROM would be seen following the HILD intervention and both the HILD and LIHD interventions would show no significant change in contralateral limb performance (isometric force, muscle activation, countermovement jump (CMJ), and drop jump (DJ) height).

Methods

Participants

A statistical power analysis of similar studies (da Silva et al. 2015; Hadjizadeh Anvar et al. 2023) was completed (G*Power 3.1.9.7) to determine a sample size of 16 participants would be needed to achieve an α value of p<0.05 with a power of 0.8. Convenience sampling was used to recruit 16 apparently healthy, trained males (n=8) and females (n=8). All participants had a minimum 1 year of resistance training experience and currently resistance train at least 3x per week. All participants did not have lower limb injuries that currently present symptoms nor undergone a lower limb surgical procedure in the past. Participants had a mean age of 21.5±1.41 years and resistance training experience of 4.4±2.5 years. Mean height of 179.68±5.49cm for males and 164.81±3.67cm for females

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and mean weight of 88.4±11.7 kg for males and 69.2±16.7kg for females were recorded. Participants were asked to maintain their regular training routine and to refrain from participating in unusually strenuous activities and consuming caffeine and recreational drugs or alcohol within 24 hours prior to each data collection session. Each participant was extensively informed of the procedure and signed an informed consent form prior to testing. Ethical approval was granted by the institution's Interdisciplinary Committee on Ethics in Human Research (ICEHR # 20241205-HK).

Experimental Design

The study consisted of a familiarization session and three testing sessions of approximately 30 minutes each, each separated by a minimum of 24 hours. During the familiarization session, participants were verbally explained, read and signed the consent form. Anthropometric measures were recorded, and the intervention and testing procedures were explained, demonstrated, and practiced. At the beginning of each testing session, participants completed a 5-minute aerobic warm-up (Monark® cycle ergometer) at 70 RPM and 1 kilopond resistance. Participants were asked to identify their dominant lower limb, defined by the lower limb used in a kicking task. SS of the dominant leg hamstrings was administered passively by a researcher as an intervention. Participants completed either 1) HILD (6x10-s at maximal POD), 2) LIHD (6x30-s at initial POD), or 3) passive control during each session. Participants were allocated a 10-s recovery period between each SS. The intervention implemented during each session was randomized. During pre- and post-test measures, measurements of dominant and non-dominant lower limbs were randomized and the order of measurement was also randomized. Both pre- and post-test, participants completed 2-3 trials of hamstrings ROM, knee flexion maximal voluntary isometric contraction (MVIC), unilateral CMJ, and unilateral DJ. A third trial was administered if the second trial was 5% greater than the first trial.

Pre- and Post-Test Measures

Hamstrings Range of Motion (ROM)

Participants were asked to lie supine on a padded table with legs extended and arms by their side. The participants' greater trochanter of the femur and lateral malleolus was then palpated, and a digital goniometer (EasyAngle®) was then placed at those points. The same researcher for each ROM measure then flexed the participant's hip passively ensuring the stretched leg's knee remained straight (extended) and the non-stretched leg remained on the table. The hip was flexed until the participant verbally communicated to the researcher that the maximal POD was reached. Two ROM measurements were completed with a third measurement if the second measure was 5% greater than the previous measurement. There was a 10 s rest period between each ROM trial. This procedure was repeated for both the dominant and nondominant lower limbs.

Knee Flexion Maximal Voluntary Isometric Contraction (MVIC) Force

Participants were seated upright in a seat with the back against a backrest and the hips at approximately 90°. The hips and trunk were secured to the seat with an adjustable strap. A cuff was placed around the ankle and connected to a chain, which was attached to a strain gauge (Omega Engineering Inc., LCCA 250, Don Mills, Ontario) in front of the seated participant. The knee was positioned at 120° of knee flexion and the ankle at 90°. As a warm-up, participants completed two knee flexion isometric contractions at approximately 50% of their maximal contraction and one contraction at approximately 90% of their maximal contraction. Each contraction was held for 3-s.

Pre-test knee flexion MVICs were performed for two trials with 1-minute rest between trials. A third trial was performed if the second MVIC was 5% greater than the first MVIC. This procedure was repeated for both the dominant and non-dominant lower limbs. Post-test knee flexion MVICs were performed in the same manner without a prior warm-up. MVIC measures were acquired by a strain gauge and digitally transferred to a data acquisition software (BIOPAC® Systems Inc.). Differential voltage (±0.03% linearity and 3 mv/V) from the strain gauges, sampled at a rate of 2,000-Hz, were calibrated (to Newtons), amplified (x1000), digitally converted (Biopac Systems Inc. DA 100

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and analog to digital converter MP100WSW; Holliston, MA), and monitored on a computer. A commercial software program (AcqKnowledge III, Biopac Systems Inc., Holliston, MA) was used to analyze the digitally converted analog data. The highest peak force of the two-three MVIC trials were used for analysis (AcqKnowledge, BIOPAC® Systems Inc.). Instantaneous strength (peak force exerted in the first 100-ms) was also extracted from the contraction with the highest force.

Hamstrings Activation (EMG)

The participants' skin in the area midway between the gluteal fold and popliteal fossa of the knee was shaved of hair, abraded using an abrasive gel, and cleaned using an alcohol swab. The distance between the gluteal fold and popliteal fossa was measured using a soft tape measure and the midpoint of the biceps femoris muscle belly was marked using a skin-safe marker. Surface EMG electrodes (Covidien Kendall™) were placed on the skin of the indicated area as reported by SENIAM recommendations (Hermens et al. 1999). The mean amplitude of the root mean square (RMS) EMG activity was recorded 0.5-s before and after the peak force of each knee flexion MVICs. All EMG signals were monitored (Biopac System Inc., DA 100: analog-digital converter MP150WSW; Holliston, Massachusetts) and recorded with a sampling rate of 2000 Hz using AcqKnowledge III, Biopac System Inc software. EMG activity was filtered with a Blackman -61 dB band-pass filter between 10-500 Hz, amplified (bi-polar differential amplifier, input impedance = 2MΩ, common-mode rejection ratio > 110 dB min (50/60 Hz), gain x 1000, noise > 5 μV), and analog-to-digitally converted (12 bit) and stored on a personal computer for further analysis.

Unilateral Countermovement Jump (CMJ) and Drop Jump (DJ) Height

Unilateral CMJ and DJ heights were recorded using a ChronoJump Boscosystem® (Australia) linear encoder software. A belt was strapped around participants' waist with the lower edge in line with the iliac crest and the linear encoder was attached to the belt at the participants left hip. The participant was instructed to stand unilaterally with hands on the hips above the belt (akimbo). For the CMJ, participants were verbally instructed by the researcher to perform a brief knee flexion (eccentric component) to a depth of their personal preference and then jump (concentric component) as high as possible landing on the same foot. Knee flexion times and depths were self-selected by the participants, however, participants were encouraged to minimize the time and depth. Hands remained on the hips throughout the jump. Two trials were completed for both dominant and non-dominant legs.

During DJ trials, the belt and linear encoder were arranged in the same manner. DJ height trials commenced by participants standing on a platform 20cm high and stepping off onto the tested leg. Participants were instructed to rebound as quickly as possible when the foot hits the ground and to minimize knee flexion time and depth during the rebound. Two trials were completed for both dominant and non-dominant legs.

Control Session

The control session was executed in the same manner as the HILD and LIHD sessions with the exception of the dominant leg SS intervention. Following pre-test measures, participants were instructed to lie supine on a padded table with arms by their side and legs straight. Participants remained in this position for 255 seconds which is equivalent to the duration of the LIHD SS intervention. Post-test measures were recorded 1 minute following the intervention.

Statistical Analysis

Statistical analyses were calculated using SPSS software (Version 28.0, SPSS, Inc, Chicago, IL). Kolmogorov–Smirnov tests of normality were conducted for all dependent variables. An α value of $P < 0.05$ was considered statistically significant. If the assumption of sphericity was violated, the Greenhouse–Geiser correction was employed. Collected data was analyzed using a repeated measure 3-way ANOVA (2 conditions x 3 interventions x 2 test times). This included 2 conditions (stretched

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leg versus non-stretched leg), 3 interventions (HILD, versus LIHD versus control), and 2 test times (pre-test versus post-test). Bonferroni post-hoc tests were conducted to detect significant main effect differences 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 (from SPSS-tutorials, 2022). 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, ^{3}0.8: large magnitude difference (Cohen 1988).

Results

Range of Motion

A significant main effect for leg ($F_{(1,14)}$ =4.71, p=0.048, eta^2: 0.25) revealed that the stretched leg demonstrated a 1.9% greater ROM (109.12±12.5^0) than the contralateral non-stretched leg (107.14±13.36^0). A significant main effect for testing time ($F_{(1,14)}$ =5.52, p=0.034, eta^2: 0.28) showed that ROM increased 1.7% from pre- (107.2±12.0^0) to post-test (109.05±13.6^o). There was a near significant leg x stretch-intensity-duration x testing time interaction ($F_{(2,28)}$ =2.74, p=0.08, eta^2: 0.16). Following the HILD condition, the post-test ROM for the stretched leg (110.6±12.6^0) exceeded the pre-test (106.0±9.0^0) by 4.2% (p=0.008). Similarly, with LIHD, the stretched leg post-test (112.2±16.5^0) also exceeded (p=0.06) the pre-test ROM (109.3±16.2^0) by 2.6% (Table 1).

Table 1. Pre- and post-test data. CMJ: countermovement jump, DJ: drop jump, HILD: High intensity, low duration, LIHD: Low intensity, high duration, IS: instantaneous strength (peak force exerted in the first 100 ms of the MVIC), MVIC: maximal voluntary isometric contraction, ROM: range of motion.

	Stretched Leg					
	HILD pre	HILD post	LIHD pre	LIHD post	Control pre	Control post
ROM (^{0})	105.3±8.6# p=0.008	109.6±12.0# p=0.008	109.2±15.1+ p=0.06	112.2±15.5+ p=0.06	107.2±11.9	107.8±11.8
MVIC (N)	350.6±99.1	360.1±101.6	349.0±101.6	336.3±114.9	354.6±100.7	347.4±108.7
MVIC EMG (mV)	0.083±0.038	0.086±0.039	0.079±0.038	0.081±0.039	0.086±0.041	0.081±0.037
IS (N)	126.1±77.4	106.8±75.4	116.5±77.6	111.8±72.5	119.2±74.8	118.1±83.5
IS EMG (mV)	0.059±0.038	0.055±0.033	0.059±0.028	0.057±0.038	0.064±0.030	0.063±0.037
CMJ (cm)	11.2±5.2	11.1±4.9	10.6±3.7	10.6±4.3	10.7±4.4	10.6±5.1
DJ (cm)	11.0±4.4	10.7±4.9	10.3±4.4	11.4±4.5* p<0.05	11.9±4.2	11.1±4.2
	Contralateral non-stretched leg					
	HILD pre	HILD post	LIHD pre	LIHD post	Control pre	Control post
ROM (^{0})	104.2±11.1	105.3±14.2	108.5±12.7	109.1±15.3	105.8±12.7	107.2±13.3
MVIC (N)	344.0±107.0	344.8±96.5	336.7±101.1	320.2±103.2	343.2±99.6	330.8±94.7
MVIC EMG (mV)	0.076±0.030	0.074±0.028	0.069±0.027	0.066±0.028	0.073±0.023	0.072±0.029
IS	104.0±83.6	112.9±75.3	103.9±74.9	113.1±82.8	113.1±82.8	108.6±85.1
IS EMG (mV)	0.061±0.059	0.051±0.029	0.045±0.025	0.045±0.028	0.052±0.032	0.049±0.030
CMJ (cm)	9.9±4.6	10.2±5.1	11.1±4.3	9.7±3.9	10.0±4.6	9.0±4.1
DJ (cm)	9.4±3.8	9.3±3.9	10.8±4.8	9.5±3.7* p<0.05	9.4±4.1	10.2±5.2

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MVIC Force and Instantaneous Strength

With peak force, there was a significant main effect for testing time ($F_{(1,13)}$ =40.13, p<0.001, eta²: 0.75) with an overall 3.7% decrease from pre- (343.1±108.4 N) to post-testing (330.6±105.7 N). With instantaneous strength, there was also a significant main effect for testing time ($F_{(1,13)}$ =10.14, p=0.007, eta²: 0.44) with an overall 10.9% decrease from pre- (114.8±80.2 N) to post-testing (102.4±77.7 N). EMG associated with instantaneous strength also revealed a significant, large magnitude, main effect for testing time ($F_{(1,12)}$ =18.31, p=0.001, eta²: 0.604) with an overall 10.2% decrease from pre- (0.059±0.036 mV) to post-testing (0.053±0.036 mV).

Unilateral Countermovement (CMJ) and Drop Jump (DJ) Height

There were no significant main effects or interactions for CMJ height. There was a non-significant main effect ($F_{(1,13)}$ =3.21, p=0.09, eta²: 0.19) for legs with DJ height with the stretched leg (10.7±4.2 cm) demonstrating a 9.4% greater jump height than the contralateral non-stretched leg (9.7±4.0 cm). A significant leg x stretching intensity x testing time interaction ($F_{(2,26)}$ =4.52, p=0.02, eta²: 0.26) for DJ showed that with LIHD, the stretched leg (10.5±3.7 cm) significantly (p=0.05) exceeded the contralateral leg (9.1±3.8 cm) by 13.4% at post-test (Table 1).

Discussion

The major findings of this study were 1) unilateral stretching did not induce contralateral effects, 2) no significant differences with the stretched leg ROM increases between HILD and LIHD SS, 3) overall, SS induced decreases in peak force, instantaneous strength and EMG, and 4) LIHD provided greater increases with the stretched leg DJ heights overall.

An increase in contralateral limb ROM is fairly consistent within the current literature (Hadjizadeh Anvar et al. 2023; Behm et al. 2016b; 2019; Chaouachi et al. 2017, Marchetti et al. 2017). The Behm et al. (2021a) meta-analysis based on 11 studies (14 independent measures) reported moderate magnitude enhancement of non-local or crossover ROM. However, these findings are not unanimous as not all studies have shown non-local ROM increases with either acute (Grabow et al. 2017) or chronic stretching (Konrad et al. 2024a;b). In contrast to the meta-analytical results (Behm et al. 2021a), the present study demonstrated no significant increase in contralateral limb ROM. The majority of studies that provide evidence of an increase in contralateral limb ROM following SS implement longer duration (>60-s) with high-intensity (maximal POD) SS which differs from the interventions of the current study (high intensity with shorter duration (HILD) vs. lower intensity with longer duration (LIHD)). For example, Hadjizadeh Anvar et al. (2023) also implemented 180-s (6x45-s) of SS resulting in a significant increase in contralateral limb ROM, but they had participants stretch to the maximum rather than initial POD as with the LIHD session of the current study. The Behm et al. (2021a) meta-analysis reported that 240-s of SS demonstrated large magnitude non-local ROM increases compared to moderate magnitude improvements with shorter (<120-s) durations. Although the SS prescriptions in this study are in accord with prior reviews (Behm 2018; Behm et al. 2015; 20121a; Behm and Chaouachi 2011; Chaabene et al. 2019; Kay and Blazevich 2012), the lack of increase in contralateral limb ROM may suggest 60-s (6 x 10-s) of SS at maximum POD (HILD) is an insufficient dosage to stimulate non-local ROM increases. Alternatively, 180-s of SS (6 x 30-s) at the initial POD (LIHD) may be an insufficient intensity to engage crossover ROM effects.

Increased stretch (pain) tolerance has been widely attributed as a primary mechanism underlying stretched and non-stretched joint ROM increases (Magnusson et al. 1996; Konrad & Tilp 2014; Weppler et al. 2010; Freitas et al. 2018; Chaouachi et al. 2017; Behm et al. 2019; Hadjizadeh Anvar et al. 2023). Increased stretch tolerance effects to increase contralateral ROM has been attributed to diffuse noxious inhibitory control (DNIC) and gate control theory of pain due to stimulation of nociceptors from the SS which may suppress the sensation of pain (LeBars et al. 1992; Behm et al. 2019. Hadjizadeh Anvar et al. 2023; Pud et al. 2009). The lower intensity SS with LIHD and the lesser duration of SS with HILD may not have elicited a sufficient stimulus for global pain modulation.

An increase in stretched leg ROM following HILD and LIHD SS is partially in accordance with recent literature examining the effects of SS (Behm 2018; Behm et al. 2016a; Kataura et al. 2017; Nakamura et al. 2021; Reid et al. 2018; Konrad et al. 2023). In two very similar studies, participants were subjected to 180-s of SS at 80%, 100%, and 120% intensities for either the hamstrings (Kataura et al. 2017) or quadriceps (Nakamura et al. 2021) and both studies reported significant increases in ROM following the 100% and 120% intensities but non-significant ROM increases following the 80% intensity SS. With both conditions in the present study, the stretched leg experienced a significant ROM increase following HILD (60-s total at maximal POD) SS as well as a non-significant (p=0.06) improvement with LIHD (180-s total at initial POD). Subgroup analyses in recent review articles (Arntz et al. 2023; Behm et al. 2023; Konrad et al. 2023) report no significant evidence that SS intensity moderates the effect of ROM. The present findings are consistent with the findings of these reviews demonstrating significant and near significant (p=0.06) increases in stretched leg ROM following both high and lower intensity SS respectively. Practical applications suggest that stretching to the maximal POD may not be required to increase ROM.

The significant, large magnitude overall (main effects for time) decrease in peak force, instantaneous strength, and muscle activation (EMG) are in accord with prior studies and reviews that warn of performance impairments with prolonged SS (≥60-s) without a full dynamic warm-up (Behm and Chaouachi 2011, Behm et al. 2016a; 2021b; Blazevich et al. 2018; Chaabene et al. 2019; Kay & Blazevich, 2008; 2012; Reid et al. 2018). A possible mechanism includes a decrease in persistent inward currents (PICs) attenuating the gain of the spinal motoneurons (Behm et al. 2021; Trajano et al. 2014; 2017; 2020; 2021). It is possible that desensitization of the muscle spindles may disfacilitate spinal motor neurons decreasing their discharge frequency adversely affecting the maximal force production (Behm et al. 2021, Trajano et al. 2014; 2017; 2021). Morphological changes such as decreases in muscle stiffness (increased compliance) have also been reported (Behm and Chaouachi 2011, Behm et al. 2016a; 2021b; Chaabene et al. 2019; Kay & Blazevich, 2012). But as this finding was a main effect for time and thus combined data from both limbs, this mechanism could not apply to the non-stretched limb. Mental energy deficits (decreased ability to focus or concentrate after an initial bout of exercise) (Halperin et al. 2015) and increases in the perception of effort after an exercise session (Steele 2021) are other alternative mechanisms. As mentioned, since these findings were a main effect for time with no significant interactions, this was an overall effect but not specific to either leg.

While there was no significant change in unilateral CMJ height, there was a significant increase in the stretched leg unilateral DJ height with a significant advantage following the LIHD intervention. Similar increases were reported by Caldwell et al. (2019) who exhibited a significant increase in stretched leg unilateral DJ height following 120-s hamstrings SS with ground contact time being significantly increased (small magnitude) as well. Decreased musculotendinous stiffness (increased compliance) can reduce the efficient transfer of force adversely affecting force development with a rapid stretch shortening cycle (SSC) (Aura and Komi 1986, Bosco et al. 1982, McCarthy et al. 2012). Alternatively, an increase in MTU compliance is conceivably beneficial for tasks that require slower eccentric contractions or a prolonged transition (contact or amortization phase) during the SSC (Chauoachi et al. 2010, Godges et al. 1989, Wilson et al. 1992).

This could be a possible mechanism for the present result as a unilateral DJ is a relatively unfamiliar movement, it is likely that the jump required a longer eccentric contraction and contact period to absorb the force compared to the unilateral CMJ. Therefore, an increased MTU compliance may have increased the ability of the MTU to store elastic energy over a greater period, leading to an improved unilateral DJ height (Behm & Chaouachi, 2011; Behm, 2019). Similarly, it is noted that an increased ground contact time during the unilateral DJ could increase the time which the force is absorbed over, increasing impulse, and thus improving unilateral DJ height (Caldwell et al. 2019). Unfortunately, ground contact time was not monitored during DJ measures. The current study seems to be in accordance with several previous studies investigating changes in MTU compliance following a single bout of SS, implying that only higher duration SS is associated with increased MTU compliance (Behm et al. 2021; Konrad & Tilp, 2020; Konrad et al. 2017; Konrad et al. 2020; Nakamura et al. 2013) with lower duration SS having minimal or no effect (Konrad et al. 2020; Nakamura et al. 2013). This may explain the significant advantage in stretched leg unilateral DJ height seen following the LIHD SS intervention.

Limitations

Every study has limitations that should be considered when interpreting the results. All studies can benefit from a greater number of participants to strengthen the power of the analysis. A great number of participants might have provided greater statistical power to possibly reveal other significant interactions. The study's findings are also limited by the specific characteristics of the sample population (resistance training for at least 1 year) and may not directly apply to other populations (e.g., sedentary adults, seniors, children, and others). The findings are also specific to the constraints inherent in the study design, including the duration and intensity of the stretching protocols and the timing of measurements. These limitations underscore the need for cautious interpretation and suggest paths for future research to enhance the validity and generalizability of findings in stretching interventions. Although the participants practiced the tests in the familiarization session, unilateral CMJ and DJ are movements many participants were unfamiliar with.

Conclusion

In summary, both a HILD and LIHD SS intervention of the dominant leg hamstrings resulted in increased stretched leg ROM (near significance for LIHD stretched leg) with no significant changes in contralateral ROM and an overall (main effect for time) decrease in unilateral force, instantaneous strength, and associated EMG. It is possible that both interventions had insufficient influence on increased stretch tolerance for the contralateral limb. LIHD induced a significant increase in the stretched leg unilateral DJ height.

Based on the findings of the present study, it is suggested that longer duration SS at a high intensity may be required to elicit increases in contralateral ROM in a resistance trained (at least 1 year) population. This may be applicable in a rehabilitation setting where a limb is immobilized for a period of time due to injury. The current findings help clarify the SS prescription to increase contralateral ROM suggesting that the prescriptions applied in this study were insufficient. Furthermore, these findings may be applied to an athletic performance setting where the goal is to maximize unilateral DJ height. Based on the current study, it is suggested that greater unilateral DJ height of the stretched leg is shown following a LIHD SS.

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