Research paper

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Acute effects of Nordic hamstring exercise on ultrasound shear wave elastography

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Abstract

Aim: The Nordic hamstring curl appears effective in reducing the incidence of injury in physically active young adults, likely through its capacity as an eccentric exercise to increase muscle stiffness. Although eccentric exercises have been shown to increase muscle stiffness, medium- and long-term Nordic hamstring curl training programs have not demonstrated an effect on muscle stiffness. This study examined the acute effects of a single session of Nordic hamstring curls on the stiffness of the biceps femoris, semitendinosus, and semimembranosus muscles using ultrasound shear wave elastography, an accepted method for measuring passive muscle stiffness. **Material and methods:** Twenty physically active adults (ages 19–27 years) were randomly assigned to either the Nordic hamstring curl group ($n = 10$) or the control group ($n = 10$). Shear wave elastography was performed on the dominant kicking leg for both groups. The exact location of the probe was marked to ensure the same area was assessed during post-testing. Both groups performed a 5-minute cycle ergometer warm-up followed by three 30-second standing static stretches. The Nordic hamstring curl group then performed three sets of six repetitions of the eccentric phase of the Nordic hamstring curl with 1-minute rest intervals between sets. All subjects then rested for five minutes before shear wave elastography was performed. **Results:** Repeated measures ANOVA revealed no significant main effects or interactions for the biceps femoris or semitendinosus ($p > 0.05$). However, analysis of the semimembranosus was inconclusive due to variability of measurement values. **Conclusions:** These results are in agreement with findings indicating that long- and short-term Nordic hamstring curl training has no impact on hamstring stiffness, although the effects of Nordic hamstring curl on reducing the probability of hamstring injury are still valid.

Introduction

During game and practice conditions, hamstring injuries comprise between 10% and 12% of the lower limb injuries sustained by athletes[1,2]. These injuries are commonly described as forceful elongations, deep stretching sensations, or tears of the posterior compartment of the thigh, which includes the biceps femoris, semitendinosus, and semimembranosus muscles[3].

Among the strategies employed to reduce the incidence of this type of injury is the Nordic hamstring curl (NHC)[4,5]. This exercise begins in a kneeling position and requires the athlete to stop their body's forward momentum using an eccentric contraction of the hamstring muscles as they lower themselves into a prone position[4]. The physiological mechanisms responsible for the effectiveness of the NHC are unclear[6], but they may include increases in eccentric strength throughout the range of motion, improved neuromuscular activation, and increased control in the performance of functional activities such as vertical jumps[7–9]. Another possible factor contributing to the protective effect of this exercise is an increase in muscle stiffness. Muscle tension can lead to injury; however, stiffer muscles experience less tension when force is applied[6]. Since strength exercises induce muscle hypertrophy and tonus, the NHC should increase the stiffness of the posterior compartment of the thigh[6]. Furthermore, it has been hypothesized that muscle stiffness may increase after an exercise session due to cellular inflammation and heightened tissue pressure; however, there is a paucity of evidence to support this hypothesis[10].

Muscle stiffness may be related to muscle quality since it has been observed that a stiffer muscle commonly presents with more muscle mass and less fat content[11,12]. Advances in musculoskeletal ultrasound technology in recent decades have allowed the widespread use of this device and its functions to contribute to scientific research[13,14]. One of the ultrasound functions, ultrasound shear wave elastography (SWE), is a recent technology employed to measure muscle stiffness. The ultrasound device generates shear waves in the tissue of interest and calculates the speed of wave propagation to quantify the stiffness or elastic modulus of the muscle. Since the stiffness of the muscle is directly proportional to the speed of wave propagation, this method allows for the calculation of the shear modulus of the muscle and the measurement of its passive stiffness[15,16].

Several studies have reported that SWE is a reliable index to measure muscle stiffness[17,18]. In studies analyzing skeletal muscle tissue, SWE showed high intra-operator reliability (0.751–0.941) and moderate inter-operator reliability (0.585–0.749) in the assessment of passive stiffness[16,19].

Studies have also shown that muscle stiffness measured by SWE increases acutely after an isolated session of eccentric exercise[20,21]. However, no previous study has confirmed this effect in the hamstring muscle group. Therefore, the purpose of this study was to examine the effect of an isolated NHC curl session on the stiffness of the biceps femoris, semitendinosus, and semimembranosus muscles using SWE. We hypothesized that the performance of the NHC would significantly increase SWE, and that SWE in the intervention group would be significantly higher compared to the control group.

Materials and methods

Participants

Twenty physically active adults (ages 19–27 years), recruited from the university community, participated in this study. The only exclusion criterion was a history of hamstring injury. The study was approved by the University's Subcommittee for the Use and Protection of Human Subjects (Study #: 20210734). Potential subjects were informed of the risks and benefits of the study and signed an institutionally approved informed consent document before enrollment in the study.

Measures

Participants were placed in a prone position (0° hip and knee flexion) on a standard athletic training table with the ankle relaxed[6]. A LOGIQ P9 R3 Ultrasound System (GE Healthcare, Buckinghamshire, UK) and 3–12 MHz linear array transducer probe were used to assess SWE. The probe was placed in a position that allowed SWE to be performed in the longitudinal position[20,22,23]. Measurements were made on the three muscles of the hamstrings (long head of the biceps femoris, semitendinosus, and semimembranosus). An example of the SWE analysis for the biceps femoris is presented in Fig. 1A, the semitendinosus in Fig. 1B, and the semimembranosus in Fig. 1C. Additionally, a transverse image of all three muscles is shown in Fig. 1D.

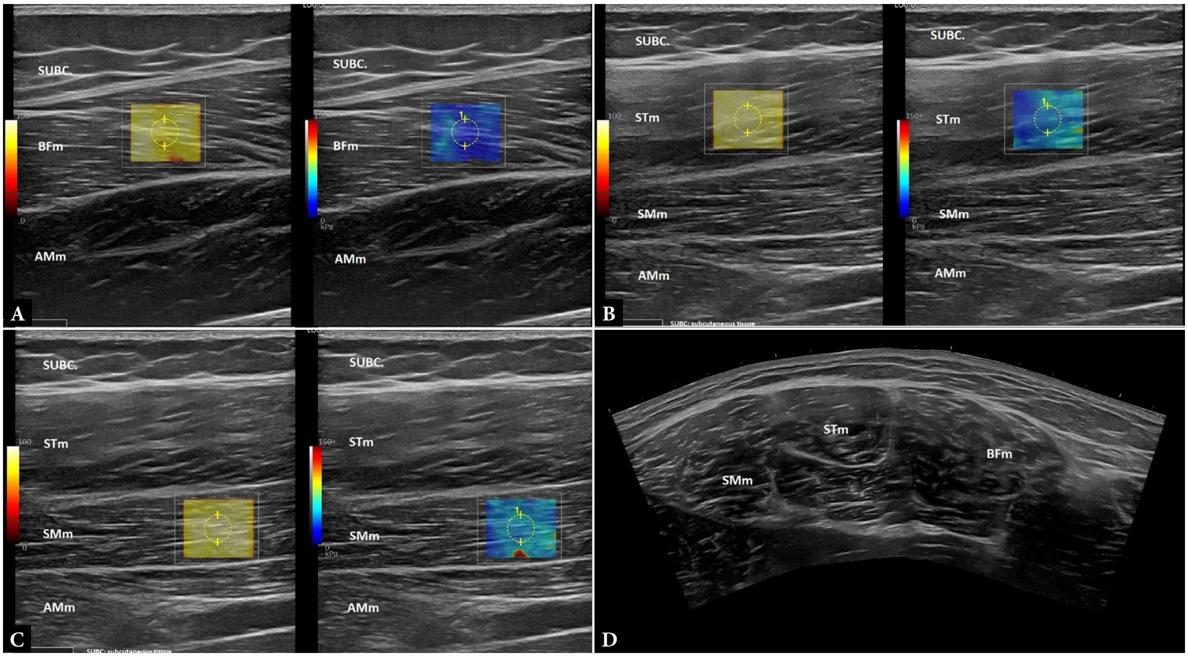

Fig. 1. *Ultrasound shear wave elastography measurements in kilopascals (kPa) and meters per second (m/s) in a longitudinal view of the biceps femoris (***A***), semitendinosus (***B***), and semimembranosus (***C***), and a transverse view of all three muscles (***D***). AMm – adductor magnus muscle; BFm – biceps femoris muscle; SMm – semimembranosus muscle; STm – semitendinosus muscle; SUBC – subcutaneous tissue*

The position of the probe for all muscles was determined using anatomical landmarks: 50% of the distance between the greater trochanter and medial femoral condyle for semitendinosus and semimembranosus, and 50% of the distance between the greater trochanter and lateral femoral condyle for the long head of biceps femoris[24]. These landmarks were measured with a spring-loaded tape measure and marked with a skin-friendly marker to allow consistent probe positioning during pre-test and post-test SWE measurements[23]. The measurements were made on the dominant (kicking) leg only[25,26]. Three images were taken during each testing session, and the means of the three SWE values were recorded[3]. Subjects were instructed to remain relaxed throughout the ultrasound examination.

The measurements were taken immediately before the exercise session and 5 minutes after the end of the session, following protocols from previous studies on other muscle groups; therefore, the post-exercise measurement was performed within 15 minutes of the end of the exercise[3,20,24].

For a better understanding of the posterior compartment of the thigh through a standardized sonographic protocol, please refer to the study by Cocco *et al.*[27].

Procedures

Shear wave elastography

Patients assigned to the intervention group performed a warm-up consisting of 5 minutes of pedaling on a cycle ergometer at a brisk pace, followed by three static stretches lasting 30 seconds each in a standing position[6]. Less stretching was used than in other studies[6] to focus more effectively on the effect that the NHC produced on elastography, as evidence suggests that passive hamstring stretching alone can decrease SWE values[24]. For the stretch, participants were asked to reach down and attempt to touch their toes while keeping their legs straight until they felt uncomfortable but experienced no pain[6].

After 5 minutes of rest, the participants performed a single bout of the NHC (Fig. 2). The bout consisted of three sets of six repetitions with 1-minute rests between sets, reflecting the protocol used in a similar population[28]. The subjects knelt on a mat during the exercise, and an investigator stabilized their legs. They were then instructed to slowly lower their torso to ground level, keeping their trunks straight and hinging only at the knees. The subjects kept their arms crossed at the chest until the final phase of the exercise, when they were allowed to use their arms to decelerate the movement so their head and torso did not hit the ground[7,28]. To return to the starting phase, the participants were instructed to use their arms, thus avoiding a concentric contraction of the hamstrings[28].

The control group performed the same warm-up as the intervention group without performing the NHC.

Randomization

Patients were randomized to the intervention or control groups using an online random number generator (random.org: https://www.random.org/).

Fig. 2. *Subject performing the Nordic hamstring curl exercise*

Blinding

No attempts were made to blind the subjects or the investigators due to the nature of the intervention.

Statistical analysis

For each muscle and measurement unit (kPa, $m \cdot s^{-1}$), separate 2 (group) × 2 (time) mixed repeated measures ANOVAs were used to determine if the NHC had an impact on SWE measurements. Statistical significance was set a priori at $p \leq 0.05$. Mauchly's Test of Sphericity was used to test whether the assumption of sphericity was met for all variables.

Results

Participants

Twenty physically active adults (ages 19–27 years) were randomly assigned to the intervention group (n = 10) or the non-intervention group (n = 10). Recruitment occurred from August 1, 2022, to September 1, 2022. A chart showing the flow of subjects through the study is presented in Fig. 3. Descriptive statistics for the entire sample and each group are provided in Tab. 1.

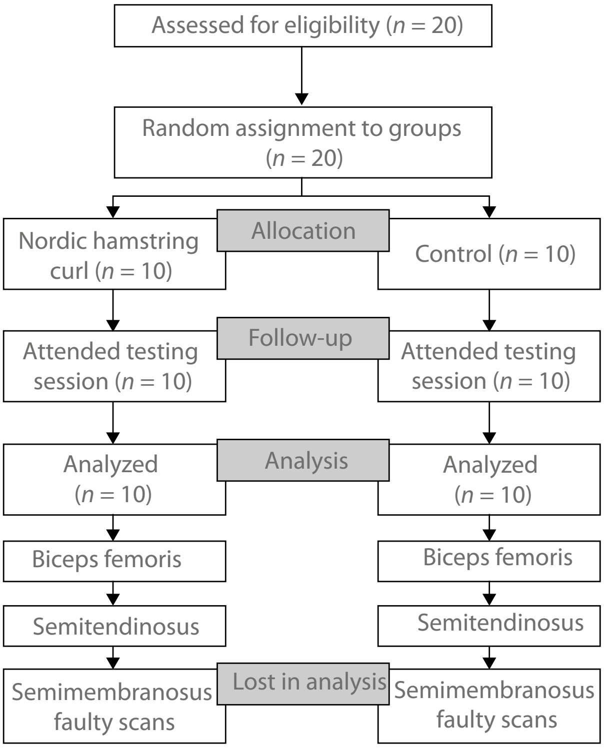

Fig. 3. *CONSORT chart showing the flow of subjects through the study*

Tab. 1. Subject characteristics

	Nordic curl (*n* = 10)	**Control (*n* = 10)**	**Sample (*n* = 20)**
Age (years)	22.1 (2.7)	20.8 (1.4)	21.5 (2.2)
Height (m)	1.70 (0.08)	1.72 (0.10)	1.72 (8.8)
Weight (kg)	65.6 (16.9)	74.0 (11.6)	69.8 (14.8)
Sex	3M, 7F	7M, 3F	10M, 10F
BMI (kg·m²)	22.3 (4.0)	24.8 (2.7)	23.5 (3.6)
% Body fat	23.3 (5.4)	24.8 (2.7)	24.3 (4.8)
Values are mean (SD). BMI – body mass index			

Shear wave elastography

No significant main effects or interactions were observed in kPa and m·s^{-1} for the biceps femoris or semitendinosus muscles. The results of the analyses of the semimembranosus could not be included because the elastography values of the semimembranosus muscle varied widely during the three pre- and post-test measurement images.

ANOVA tables for the elastography results for the biceps femoris and semitendinosus in kPa and m·s^{-1} are presented in Tab. 2A, Tab. 2B, Tab. 2C, and Tab. 2D, respectively. Furthermore, pairwise comparisons for each muscle and measurement unit are presented in Tab. 3A, Tab. 3B, Tab. 3C, and Tab. 3D. Finally, for the biceps femoris and semitendinosus in kPa and m·s^{-1}, Fig. 4 presents the means and standard deviations, as well as line and scatter plots for each subject, for pre-test and post-test values.

Discussion

To the best of our knowledge, this study is the first to evaluate the acute effects of a single bout of the NHC on muscle stiffness us-

Tab. 2A. Sum of Squares table for muscle stiffness of the biceps femoris in kilopascals (kPa)

Source	**Type III sum of squares**	**df**	**Mean square**	**F**	***P***	**Partial eta squared**
Time	8.372	1	8.372	1.326	0.265	0.069
Time*group	13.363	1	13.363	2.116	0.163	0.105
Error (time)	113.658	18	6.314			
Group	0.416	1	0.416	0.037	0.850	0.002
Error (group)	204.499	18	11.361			
Total	343.497	39	40.307			
df – degrees of freedom ; F (Fisher statistic) – ratio of the variation between the sample means and the variation within the samples						

Tab. 2B. Sum of Squares table for muscle stiffness of the biceps femoris in meters per second (m·s^{-1})

Source	**Type III sum of squares**	**df**	**Mean square**	**F**	***P***	**Partial eta squared**
Time	0.097	1	0.097	1.717	0.207	0.087
Time*group	0.111	1	0.111	0.178	0.099	1.968
Error (time)	1.017	18	0.057			
Group	0.010	1	0.010	0.091	0.766	0.005
Error (group)	1.954	18	0.109			
Total	3.189	39	0.481			
df – degrees of freedom ; F (Fisher statistic) – ratio of the variation between the sample means and the variation within the samples						

Tab. 2C. Sum of Squares table for muscle stiffness of the semitendinosus in kilopascal (kPa)

Source	Type III sum of squares	df	Mean square	F	*P*	Partial eta squared
Time	20.895	1	20.895	1.009	0.328	0.053
Time*group	30.678	1	30.678	1.482	0.239	0.076
Error (time)	372.657	18	20.703			
Group	70.942	1	70.942	1.163	0.295	0.061
Error (group)	1097.534	18	60.974			
Total	1592.706	39	204.192			
df – degrees of freedom ; F (Fisher statistic) – ratio of the variation between the sample means and the variation within the samples						

Tab. 2D. Sum of Squares table for muscle stiffness of the semitendinosus in meters per second ($m \cdot s^{-1}$)

Source	Type III sum of squares	df	Mean square	F	*P*	Partial eta squared
Time	0.155	1	0.155	1.279	0.273	0.066
Time*group	0.066	1	0.066	0.548	0.469	0.030
Error (time)	2.182	18	0.121			
Group	0.477	1	0.477	1.668	0.213	0.085
Error (group)	5.151	18	0.286			
Total	8.031	39	1.105			
df – degrees of freedom ; F (Fisher statistic) – ratio of the variation between the sample means and the variation within the samples						

Tab. 3A. Pairwise comparisons for shear wave elastography of the biceps femoris in kilopascals (kPa)

Group	Pre-test	Post-test	Mdiff (SE)	95% CI	*P*	d
NHC	8.762 (3.057)	9.003 (2.235)	0.241 (1.124)	−2.120, 2.602	0.833	0.09
Control	9.741 (3.723)	7.643 (2.673)	−2.071 (1.124)	−4.432, 0.290	0.082	0.65
Pre-test and Post-test values are Means (SD); SE – standard error; CI – confidence interval; d – Cohen's d; NHC – Nordic hamstring curl						

Tab. 3B. Pairwise comparisons for shear wave elastography of the biceps femoris in meters per second ($m \cdot s^{-1}$)

Group	Pre-test	Post-test	Mdiff (SE)	95% CI	*P*	d
NHC	1.701 (0.320)	1.708 (0.242)	0.007 (0.106)	−0.216, 0.230	0.948	0.02
Control	1.775 (0.307)	1.571 (0.274)	−2.04 (0.106)	−4.27, 0.019	0.071	0.67
Pre-test and Post-test values are Means (SD); SE – standard error; CI – confidence interval; d – Cohen's d; NHC – Nordic hamstring curl						

Tab. 3C. Pairwise comparisons for shear wave elastography of the semitendinosus in kilopascals (kPa)

Group	Pre-test	Post-test	Mdiff (SE)	95% CI	*P*	d
NHC	16.706 (7.444)	13.509 (5.007)	−3.197 (2.035)	−7.472, 1.078	0.134	0.50
Control	17.618 (5.129)	17.924 (7.520)	0.306 (2.035)	−3.969, 4.581	0.882	0.05
Pre-test and Post-test values are Means (SD); SE – standard error; CI – confidence interval; d – Cohen's d; NHC – Nordic hamstring curl						

Tab. 3D. Pairwise comparisons for shear wave elastography of the semitendinosus in meters per second ($m \cdot s^{-1}$)

Group	Pre-test	Post-test	Mdiff (SE)	95% CI	*P*	d
NHC	2.304 (0.528)	2.098 (0.403)	−0.206 (0.156)	−0.533, 0.121	0.202	0.44
Control	2.441 (0.361)	2.398 (0.492)	−0.043 (0.156)	−0.370, 0.284	0.786	0.10
Pre-test and Post-test values are Means (SD); SE – standard error; CI – confidence interval; d – Cohen's d; NHC – Nordic hamstring curl						

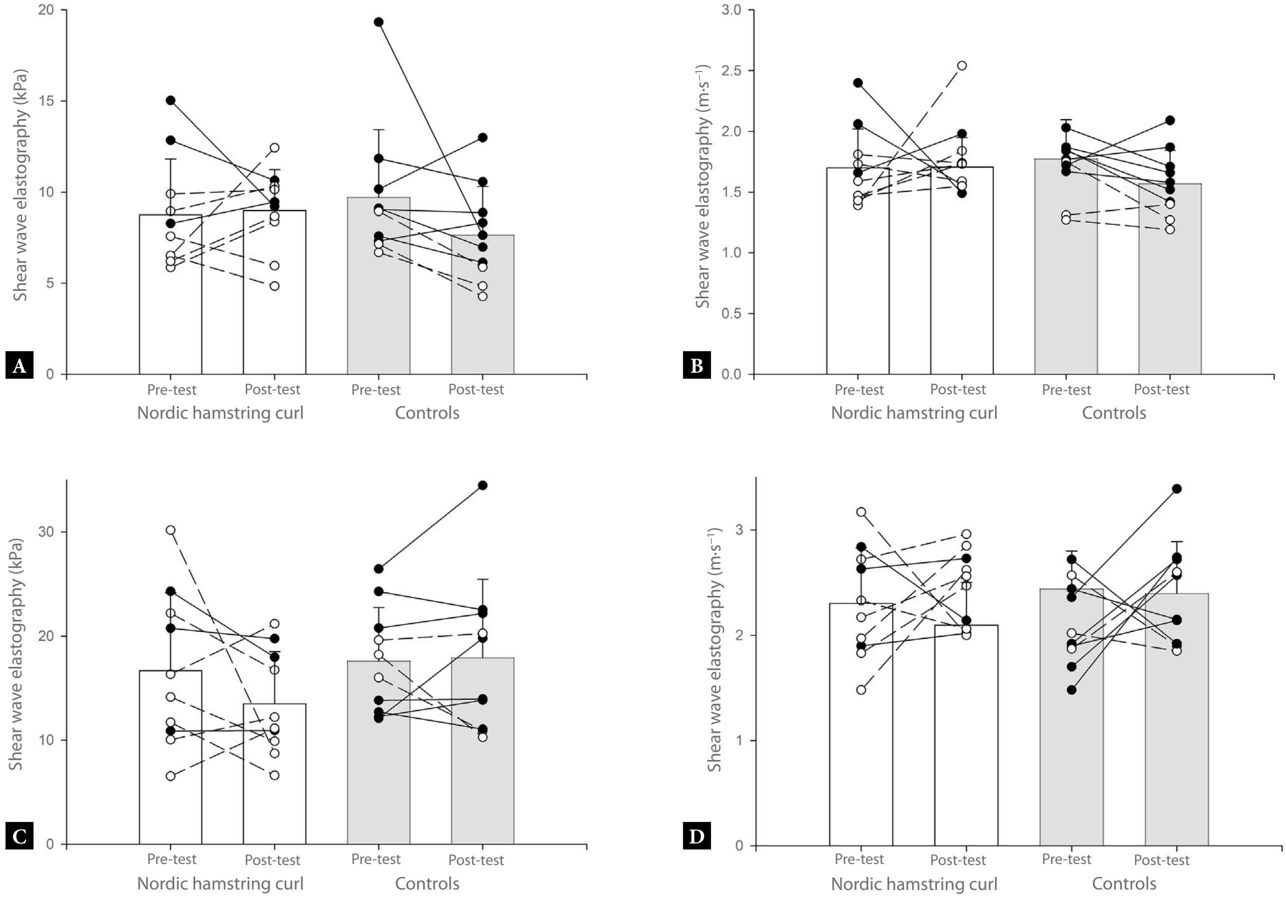

Fig. 4. *Bar graphs of means and standard deviations for pre-test and post-test values and subjects' individual scatter and line plots for Nordic hamstring curl and control groups for elastography results of* **A.** *biceps femoris in kilopascals (kPa),* **B.** *biceps femoris in meters per second ($m{\cdot}s^{-1}$),* **C.** *semitendinosus in kilopascals (kPa),* **D.** *semitendinosus in meters per second ($m{\cdot}s^{-1}$). Closed circles with solid lines indicate men, and open circles with dashed lines indicate women*

ing SWE, with minor modifications to the methodologies reported in previous studies[6,7,28]. Our study results showed no significant changes in muscle elasticity over time or between the NHC and control groups after a single acute bout of exercise. However, pairwise comparisons for the biceps femoris showed little change in stiffness for the NHC group, while reductions in stiffness by the control group approached significance (Tab. 3A and Tab. 3B). In contrast, pairwise analyses for the semitendinosus showed greater reductions in tension by the NHC group than by the controls (Tab. 3C and Tab. 3D). Additionally, the responses of the individuals in each group were not consistent, and did not appear to be sex-dependent (Fig. 4).

In contrast to studies on other muscle groups, which reported an acute increase in muscle stiffness in the biceps brachialis and gastrocnemius following a single bout of eccentric exercise[3,20], our results showed no significant changes in the SWE of the biceps femoris or semitendinosus for either group after the bout of the NHC. The training loads and volumes employed, the muscles targeted in previous studies, and the use of a stretching protocol to precondition the muscles before the NHC and control, may explain the variations in results between our study and earlier studies. The subjects in the study by Agten *et al.*[20] performed three sets of 12 repetitions of eccentric elbow flexion at 90% 1RM using their non-dominant arms, while those in the study by Leung *et al.*[3] completed 10 sets of 15 repetitions of the eccentric heel drop exercise using their dominant legs, with neither study employing any stretching as part of their testing protocol. In contrast, our intervention involved three sets of 6 repetitions using the subjects' upper body weight applied eccentrically to both legs, a 5-minute warm-up on a cycle ergometer, and three 30-second static stretches in a standing position. Therefore, the higher training loads and volumes used in previous studies, along with targeting different muscle groups and the lack of stretching could have produced much different outcomes than those seen in the current study. For example, Agten *et al.*[20] attributed the muscle stiffness immediately after exercise in his subjects to extracellular muscle edema and increased blood flow resulting from the eccentric overload. However, in his comparisons of damage to the knee extensors and flexors and elbow extensors and flexors with comparative eccentric overloads, Chen *et al.*[29] noted that the knee flexors used in the current study were much less susceptible to muscle damage than the elbow flexors that were exposed to eccentric overloads in the study by Agten *et al.*[20]. Furthermore, Jones *et al.*[30] reported that the triceps surae group, examined for stiffness changes by Leung *et al.*[3], showed shifts in the optimal angle for toque production indicative of damage immediately following eccentric training of the plantar flexors. These results also indicate the lower susceptibility of the knee flexors to exercise-induced stiffness related to immediate eccentric damage compared to the triceps surae group.

The level of muscle training is related to the levels of damage following a bout of eccentric exercise[31]. Therefore, another explanation for the differences between studies could be that our subjects were physically active young adults (21.5 ± 2.2 y), in whom a single bout of the NHC may not have provided sufficient overload to produce the acute changes expected in muscle stiffness. In contrast, the participants of the study by Agten *et al.* (2017)[20] averaged 35.1 ± 9.1 years and had no previous resistance training experience. The subjects in the study by Leung *et al.*[3], though young (21.2 ± 1.3 y), also lacked resistance training experience.

Finally, the impact of the warm-up and stretching protocols on our results must be considered. The increase in muscle temperature and stretching likely increased the compliance of the muscle and connective tissue of both muscles prior to the NHC and control testing. An examination of the secondary analyses of data using pairwise comparisons shows different results for the two muscles tested. These variations may be explained by the position of each muscle relative to the forces applied during the NHC. The biceps femoris long and short heads originate from the ischial tuberosity and linea aspera, respectively, with a common insertion at the head of the fibula. In contrast, the semitendinosus has its origin at the ischial tuberosity and inserts at the anterior proximal tibial shaft. The forced plantar-flexed position of the ankles during the NHC may have induced internal tibial rotation, resulting in greater tension on the biceps femoris than the semitendinosus, producing these differences.

Although no studies examining muscle stiffness in hamstrings using SWE after an acute bout of the NHC were found, we identified two studies[6,26] that measured the medium- and long-term effects of the NHC on muscle stiffness. These studies also involved physically active young people and similar interventions. However, in these studies, the NHC protocol used increasing loads during a six-week intervention. One study utilized a glider exercise in addition to the NHC and an extended warm-up consisting of three minutes of stepping on a 40 cm high stepper, ten squats, single leg deadlifts, lunges, front bending, and hip thrusts[26]. The second study incorporated a warm-up, which consisted of five minutes on a cycle ergometer at a brisk pace, followed by one set each of standing, seated, and supine static hamstring stretches held for 30 seconds[6]. Despite the differences in methodologies employed by these studies and our acute study, none found significant changes in muscle stiffness using SWE. Additionally, Seymore *et al.*[6] reported a significant improvement in muscle hypertrophy due to their eccentric training program, while Vatovec *et al.*[26] reported a significant increase in passive hip flexion range of movement.

Since no significant changes in muscle elasticity were seen over time or between the NHC and control groups due to a single, acute bout of exercise, our results do not support the hypothesis that performing the NHC before competition or practice would increase muscle stiffness as a mechanism to reduce injury. However, given that the NHC may diminish the risk of hamstring injury, its use as an exercise to reduce the probability of hamstring injury is still warranted, though the mechanisms by which these protective effects are achieved remain unclear.

Some limitations should be acknowledged when considering the results reported in this study. The first is the sample size, which was relatively small; however, given the effect sizes seen, ranging from $\eta_p^2 = 0.050$ to 0.142 for non-significant findings, it is doubtful that increasing the sample size would have impacted the results substantially. Second, the small training load used may have been insufficient to induce changes in our sample of physically active young people; therefore, we suggest that this study be repeated using some form of external loading. Lastly, this study measured one variable, SWE, preventing observations of the relationships between this and other variables, such as muscle girth, muscle quality, or pennation angle, which may have impacted our results.

Conclusions

A single acute bout of the NHC exercise had no impact on hamstring stiffness measured using ultrasound SWE. However, given that the NHC may diminish reduce the risk of hamstring injury, its use as an exercise to reduce the probability of hamstring injury is still warranted, though the mechanisms underlying these protective effects remain unclear. While secondary analyses indicated that both the stretching and NHC portions of the protocol may have affected muscle stiffness, we are unable to attribute these findings specifically to changes in the stiffness of the muscle tissue or the associated connective tissues or fascia.

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Information about the conflict of interest

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Author contributions

Original concept of study: RCC, SM, JP. Writing of manuscript: RCC, KJM, SM. Analysis and interpretation of data: JFS. Final acceptation of manuscript: RCC, ARC, JFS. Collection, recording and/or compilation of data: RCC, KJM, CPC, SM, JP, ARC. Critical review of manuscript: KJM, JFS.

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