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The Effects of Supplementary Low-Volume Nordic Hamstring Exercise Training on Flexibility, Mechanical Properties, and Hamstring Strength in Recreationally Active Individuals: A Randomized Controlled Trial

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Abstract

Background: We assessed the effects of a 6-week, low-volume Nordic hamstring exercise (NHE) intervention on hamstring flexibility, muscle mechanical properties and eccentric and isometric isokinetic knee flexion strength in recreationally active adults. **Methods:** Eighteen recreationally active adults were randomized into an NHE intervention group (IG; $n = 9$; females/males: 3/6; mean $\pm$ SD, age: 24.1 ± 1.3 years) and control group (CG; $n = 9$; females/males: 5/4; mean $\pm$ SD, age: 23.5 ± 1.8 years). The NHE intervention involved a progressive, supplementary training program performed initially one (weeks 1 and 2) and then two times per week over a 6-week period. The number of repetitions per session increased from 15 to 36 repetitions/week. The CG maintained their usual exercise routine over the same period. Standard goniometry, myotonometry, and isokinetic dynamometry ($60^\circ/\text{s}$) were used to measure hamstring flexibility, muscle properties and isometric and eccentric isokinetic strength prior to and five days following the intervention. **Results:** The Linear Mixed Methods analysis identified a significant group $\times$ time interactions for isometric torque (IG: +5% vs. CG: -12% , $p = 0.022$) and flexibility (IG: +1% vs. CG: +7%, $p = 0.023$). Peak eccentric torque (IG: +7% vs. CG: -7% , $p = 0.053$) and muscle mechanical properties remained unchanged over the intervention period. **Conclusions:** Six weeks of low-volume NHE training marginally improved isometric and eccentric hamstring strength in recreationally active adults without changing hamstring flexibility or mechanical properties. The findings may have important implications for performance enhancement and hamstring injury risk reduction during high-intensity recreational sports.



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1. Introduction

Nordic hamstring exercises (NHEs), which are also known as Nordic curls, are a form of eccentric resistance training in which the hamstring muscles are primarily used to control

the forward movement of the trunk during kneeling [1]. NHEs have been shown to halve the rate of hamstring injuries across multiple sports and athlete groups [2]. NHEs are typically, though not exclusively [3], performed with the hamstring muscles maintained in a relatively shortened state by maintaining the hip in an extended position throughout the forward movement [4]. Electromyographic studies have shown that NHEs elicit a high level of muscle activation, exceeding that of other common hamstring resistance exercises [5], thereby confirming their status as a high-demand exercise. The reduction in injury incidence is commonly attributed to improved capacity to tolerate high eccentric loads during sprinting, accompanied by architectural adaptations (e.g., increased fascicle length and/or a shift in the muscle's operating range toward longer lengths), which may reduce peak strain during high-speed running [2,6]. Although NHEs have been shown to be an effective strategy for lowering the incidence of hamstring strain injuries in many sports, practitioners still disagree about whether a low or high volume of NHEs is required [7].

Nunes et al. [8], in a recent umbrella review, suggested that NHE interventions demonstrated positive aggregate effects on muscle activation (>60–128% Maximum Voluntary Isometric Contraction), eccentric strength (10–15% increase in peak eccentric torque), and muscle architecture (fascicle length, muscle thickness, and pennation angle). However, one of the known limitations associated with the use of NHEs involves participation non-compliance secondary to muscle soreness. Eccentric contractions associated with NHE programs have been shown to result in considerable muscle damage, which may subsequently result in delayed onset muscle soreness [9], a common complaint particularly with the initiation of NHE programs [10]. Hence, reductions in the initial NHE volume have been proposed so as to reduce muscle soreness and thus aid compliance [11]. For instance, Cuthbert et al. [12] reported that low volumes of NHEs (≈ 20 repetitions/week) produced comparable improvements in eccentric strength to higher volumes (≈ 70 repetitions/week), while potentially facilitating greater compliance. However, their meta-analysis included studies with markedly mixed populations with diverse activity levels, ranging from sedentary to professional athletes, which resulted in high variability and thereby likely lowered the overall sensitivity of the analysis [12].

More recently, Chorp and Zemková [13] in their meta-analysis concluded that high-volume NHE interventions significantly improved peak eccentric hamstring strength and increased the thickness and fascicle length of the long head of the biceps femoris muscle without appreciable effects on pennation angle. In contrast, low-volume NHE protocols elicited a significant increase in eccentric strength, albeit with a lower effect size and no changes in muscle architecture. Therefore, systematic reviews suggest that well-trained athletes may require longer training periods and higher volumes to achieve adaptations, whereas lower volumes may be sufficient in less trained individuals [7,8,14].

Although eccentric exercise has been shown to acutely influence muscle flexibility, tissue properties and joint range of motion immediately following exercise [15,16], evidence regarding longer-term effects on hamstring flexibility remains inconsistent [17]. Eccentric hamstring exercises, such as straight leg or Romanian deadlifts, performed at longer muscle lengths may promote greater flexibility adaptations than those performed at shorter lengths [18–22]. Indeed, studies evaluating eccentric training protocols in which the hamstring muscle is exercised at lengthened states have typically, though not exclusively, noted improvements in hamstring flexibility (in the order of $4\text{--}12^\circ$) in healthy young adults, often without accompanying changes in passive musculotendinous stiffness [20]. Those involving standard NHE protocols, in contrast, have reported mixed results, with either large improvements ($+12^\circ$) noted following low-volume (72 total repetitions) protocols [11] or no improvements observed in hamstring flexibility even following high-volume (186–736 total repetitions) training protocols spanning a 4-to

10-week duration [1,23]. Hence, further research evaluating the effect of low-volume NHEs on hamstring flexibility seems warranted [11].

To date, the majority of research evaluating the effect of NHEs has arguably focused on amateur, semi-professional or professional athletes, and there is a lack of knowledge regarding the effects in healthy, recreationally active adults [8]. The aim of the current study, therefore, was to assess the short-term effects of including a supplementary, 6-week, low-volume NHE training program on hamstring strength, flexibility and tissue properties in recreationally active adults, compared to routine training. Given the predominance of neural adaptations that enhance strength during the early phase of resistance training [24–26], which do not appear to require substantial volume stimuli [27], we hypothesized that the NHE program would stimulate increases in peak isometric and eccentric knee flexion torque in recreationally active adults without an appreciable influence on hamstring flexibility or muscle mechanical properties.

2. Materials and Methods

2.1. Experimental Approach

A single-blinded, randomized, controlled study design was used to determine the effects of a 6-week NHE training program on eccentric and isometric isokinetic knee flexion strength, as well as hamstring flexibility and muscle mechanical properties. Online software (Research Randomizer, version 4.0) was used to randomly allocate healthy participants to one of two equal-sized groups, a control group (CG) and an intervention group (IG) [28]. The IG received a progressive, low-volume NHE training program over a 6-week period. Both the IG and CG were required to maintain their regular lower limb resistance training and sports participation levels over the period. Outcome measures were performed five days prior to and following the 6-week program and control period [23]. Although it was not possible to conceal group allocation from participants, all outcome assessments were undertaken by a single operator in a blind manner.

2.2. Participants

This study was conducted in accordance with the Declaration of Helsinki and received clearance from the University Research Ethics and Integrity Committee (approval code: UG2022_011). All participants provided informed written consent following a verbal and written explanation of the purpose of this research, the experimental procedures to be undertaken and the benefits and foreseeable risks associated with participation.

The study sample size was calculated a priori based on previously published data for eccentric isokinetic hamstring strength reported following a similar 6-week NHE program (standardized mean difference (SMD) = 1.0) in healthy, recreationally active, young adults [29]; a population comparable to that targeted in the present study. A total sample size of 18 participants (9 per group) was estimated to provide adequate statistical power (80%; $\alpha \leq 0.05$) to detect a 15% between-group difference in peak eccentric isokinetic hamstring strength. Accordingly, this study was powered to detect mean differences in knee flexor strength during the NHE comparable to those reported in recent meta-analyses evaluating NHE interventions in both athletic (SMD = 0.96) and non-athletic populations (SMD = 1.03) [14]. In addition, this study was sufficiently powered to detect differences in muscle stiffness of a similar magnitude to those previously reported in injured but fully rehabilitated hamstring muscles (SMD = 1.23) [30].

Participants were recruited via public advertisements in the local community and social media. Potentially eligible participants took part in a telephone interview to further determine eligibility, and those who matched the criteria were invited to attend a physical examination during which eligibility was confirmed. Inclusion criteria required that all

participants were free of injury and physically active, participating in moderate-to-high-intensity recreational activities (>1.5 h) at least 3 times per week for the past 6 months. Exclusion criteria comprised (i) individuals who had undergone NHE training within the past 6 months, (ii) those with a history of hamstring strain injuries within the past 6 months, and (iii) those with a medical history of illness or orthopedic injury that could interfere with measurements.

2.3. NHE Intervention

All NHE training was conducted under the supervision of a certified strength and conditioning specialist. Participants were requested to kneel on a platform in which their feet and ankles were fixed, with their knees hip-width apart and arms crossed in front of their chest. Then, each participant was instructed to slowly lean forward while maintaining their hips and torso extended and to control the forward trunk movement through an eccentric contraction of the hamstrings. Participants were instructed to use their hamstrings equally between limbs to resist the forward-falling motion for as long as possible, with a minimum time under tension of approximately 3 s [31]. When controlled movement was no longer possible, participants were instructed to brace their fall with their hands and use their arms, rather than hamstring contraction, to return to the original starting position (Figure 1) [32]. The supervising investigator provided verbal encouragement during each repetition to maximize effort.

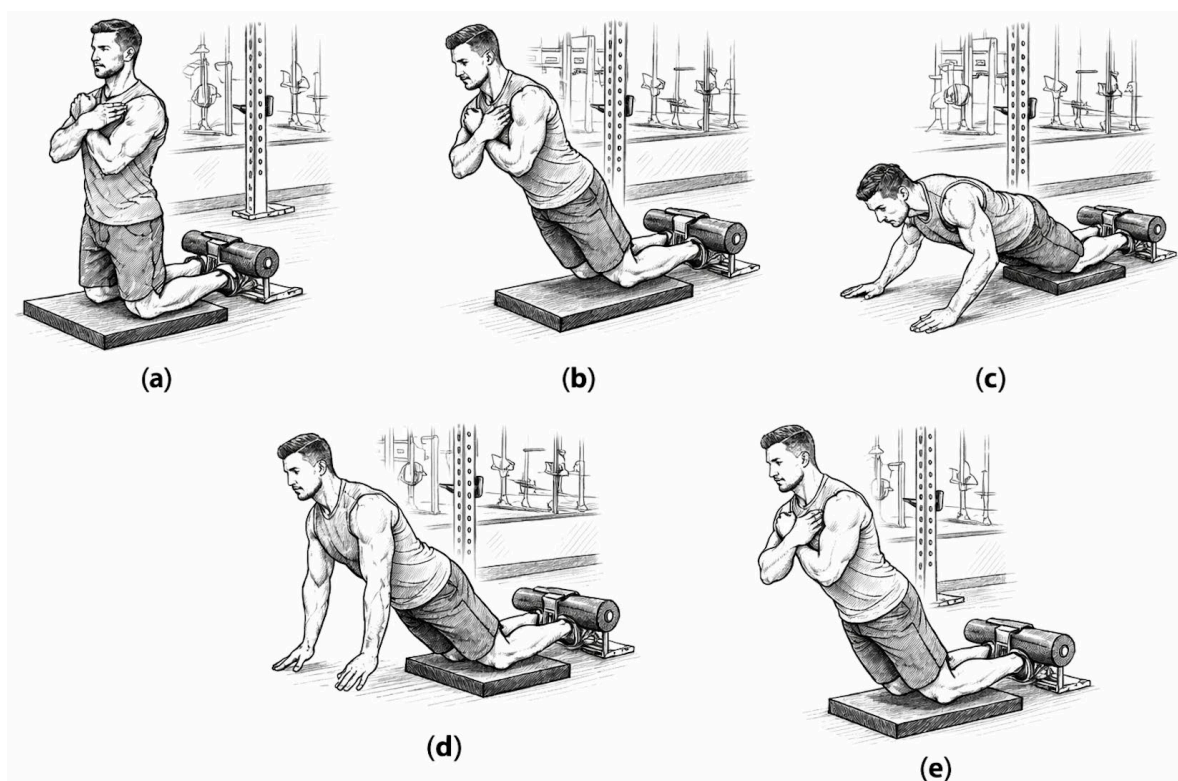


Figure 1. An illustration of one repetition of the Nordic hamstring exercise. (a) Participants knelt on a platform with their feet and ankles fixed and arms crossed in front of their chest. (b) Participants controlled a slow forward movement of the torso through an eccentric contraction of both hamstring muscles while keeping their hips and torso extended. (c) When controlled movement was no longer possible, participants braced their fall with both hands. (d) Participants then used their arms to return to an upright position, (e) before reassuming their initial starting position.

In accordance with the recommendations of Franke et al. [14], a progressive, low-volume training program was implemented, in which participants systematically increased exercise volume from 15 to 36 repetitions per week, over a 6-week period (Table 1). During each training session, the supervisor assessed participants' ability to control the eccentric phase of the movement and mean movement velocity through visual observation. To ensure the maximum effort during all testing and training sessions, verbal encouragement was provided, with a 30 s rest between repetitions and a 2 min rest between sets.

Table 1. Eccentric Nordic hamstring exercise training program.

Week	Weekly Frequency	Sets	Repetitions	Volume
1	1	3	5	15
2	1	3	6	18
3	2	2	5	20
4	2	2	6	24
5	2	3	5	30
6	2	3	6	36

Outside of the supplementary NHE program, all participants in the IG were instructed to maintain their usual exercise regimen and refrain from undertaking additional exercises that emphasized eccentric hamstring contraction. Similarly, participants in the control group were instructed to refrain from performing the Nordic hamstring exercise during the intervention period but were required to maintain their regular lower limb resistance training and sports participation, in accordance with the same activity guidelines as the intervention group (i.e., refraining from eccentric hamstring exercises that were not performed prior to the intervention). None of the participants had previously undertaken Nordic hamstring exercise training.

Self-reported logbooks, training diaries and registers were used to assess compliance with the supervised training program; to identify recreational activities that were undertaken throughout the intervention period; and to identify possible adverse events, their severity and relatedness to the intervention.

2.4. Procedures

Biomechanical outcome measures were undertaken five days prior to and following a 6-week NHE intervention period. Participants presented to a thermo-neutral laboratory on the day of testing, wearing lightweight, comfortable clothing and having abstained from vigorous physical activity, caffeinated beverages and the use of analgesics or muscle relaxants within the previous 48 h. On arrival, all participants completed the Physical Activity Readiness Questionnaire (PAR-Q). Standard demographic characteristics including stretch stature and body mass were then recorded using a stadiometer (Seca213, Seca, Hamburg, Germany) and a digital scale (Seca808, Seca, Hamburg, Germany), respectively. Lower limb dominance was subsequently determined for each participant, with the dominant leg defined as that preferred for kicking a ball [33]. Participants then performed a 10 min standardized warm-up, consisting of pedaling on a cycle ergometer (Star Trac spinner NXT, Core Health & Fitness, Irvine, CA, USA) at 80 rpm for 9 min followed by 1 min at 70 rpm.

2.5. Outcome Measures

Eccentric knee flexion strength of the dominant leg was the primary outcome measure, with isometric knee flexion strength, hamstring flexibility, and muscle mechanical properties forming the secondary outcomes. The order of outcome measures was randomized between participants to minimize potential order effects.

2.5.1. Hamstring Flexibility Assessment

The flexibility of the muscles of the posterior chain was estimated in the dominant limb of participants by a single operator using clinical goniometry (IDASS Fitness Ltd., Galstonbury, UK). Measurements were made using an established straight leg raise protocol [34]. The participant was positioned supine on the measurement plinth with their low back and sacrum directed flat against the thinly padded surface. With one hand, the operator firmly applied pressure to the thigh of the non-dominant limb to limit posterior pelvic tilt. With the opposite hand, the operator then grasped the posterior calcaneus of the dominant limb while simultaneously lifting the leg to flex the hip while retaining the knee in a fully extended position. The lower extremity was raised until firm resistance to hip flexion was detected and confirmed by the participant. Particular care was taken to ensure that no movement of the non-dominant limb occurred, and strapping was applied as required [35]. The 360° goniometer was then used to measure the angle subtended by the long axis of the trunk and thigh. Hamstring flexibility was measured in triplicate, with the highest value used for later statistical analysis. The relative reliability for repeated measures of hamstring flexibility using the method is well documented, with ICC values typically ranging between 0.93 and 0.98 [34–36].

2.5.2. Tissue Mechanical Properties

The mechanical properties of the posterior muscle chain of the dominant limb were estimated using myotonometry (MyotonPRO, Myoton AS, Tallin, Estonia), according to a previously outlined method [37]. Participants were positioned prone on a plinth, with a pillow placed beneath the ankle joint to relax the muscles of the posterior chain. The long head of the biceps femoris muscle was then identified, using the palpation technique outlined by Reichert & Stelzenmueller [38], and the midpoint marked with an indelible skin marker. The probe of the myotonometer was positioned perpendicular to the skin surface, and a train of five mechanical impulses was delivered percutaneously at a pre-determined force of 0.4 N (tap time 15 ms with an interval of 0.8 s and a delay of 0.7 s per tap). The device is fitted with real-time guidance features which ensure the application of a consistent compression force, along with the detection of any unwanted movement and muscle activation [39]. Subsequent radial tissue oscillations were automatically recorded via the tri-axial accelerometer integrated within the probe and were used to estimate key tissue parameters, including oscillation frequency, the so-called ‘dynamic stiffness’, the logarithmic decrement and the mechanical stress relaxation time of the tissue. According to Núñez et al. [40], the dynamic stiffness (N/m) of the tissue is estimated from the peak applied force and maximum tissue displacement (double integral of acceleration), while oscillation frequency (Hz), which is thought to reflect the passive (non-neural) component of resting muscle tone, is determined within the frequency domain as the frequency with peak power. Viscoelastic tissue properties were estimated based on two parameters: logarithmic decrement and mechanical stress relaxation time. The logarithmic decrement, which is thought to reflect tissue elasticity, is determined over two natural tissue oscillations using the standard linear attenuation coefficient, while the stress relaxation time of the tissue, estimated as the time to the first peak acceleration, is thought to reflect the viscous (time-dependent) component [41]. Near-real-time coefficient of variation (CV%) values for each parameter were inspected and the measurement repeated if the CV% of any parameter was higher than 3% [42]. All measurements were undertaken by a single operator trained in the use of the device and were performed in triplicate. The relative reliability for repeated measures of the ‘stiffness’ parameter over the midpoint of the biceps femoris muscle is well defined in adults, with a recent systematic review of 48 studies (1673 participants) demonstrating ICC values between 0.86 and 0.99 [43].

2.5.3. Knee Flexor Strength

Isometric and eccentric hamstring strength were measured using an isokinetic dynamometer (Cybex HUMAC2015 Norm, Computer Sports Medicine Inc. (CSMi), Stoughton, MA, USA). Following calibration of the device (Software HUMAC2015.000.025), all participants completed a series of five familiarization trials under two separate configurations. For the eccentric contraction, a standard seated position was used, in which the hip and knee were flexed to 85° and 90°, respectively [44]. Knee range of motion was set to 90°. Given that eccentric knee flexor strength is reportedly insensitive to isokinetic speed [45–47], an angular velocity of 60°·s^{−1} was used for all eccentric trials, thereby minimizing potential inertial effects [48]. Participants completed two sets of three maximal repetitions of eccentric knee flexion. Each repetition was interspersed by a passive concentric knee flexion repetition at 60°·s^{−1} designed to return the crank arm of the dynamometer to the start position while requiring no effort by the participant [46]. A 2-min rest period was afforded between sets. The mean of the peak isokinetic peak torque in each set was calculated [49] and normalized to body mass [50] for later statistical analysis.

The isometric protocol employed a similar seated position to the eccentric protocol but with the knee fixed to 45° of flexion. Participants completed two sets of three maximal repetitions of isometric contraction over a 5-s period [51]. A 2-min rest was provided between sets. Peak torque was recorded and normalized to body mass [50].

In each test, the set-up of the dynamometer was individually adjusted to each participant in line with the manufacturer's guidelines, with the lever arm aligned with the axis of rotation of the knee joint and the cuff secured around the ankle proximal to the malleoli. In all cases, restraints were used across the thigh, waist and chest to minimize the contribution from the contralateral leg and the trunk. All testing was performed on the dominant leg, and no performance feedback was provided during any of the experimental trials [44]. Correction for the effects of gravity were applied individually using a passive gravity correction curve approach, in which dynamometer data were collected during passive isokinetic motion over the entire range of motion [52]. A 10 min rest period was given between the two configurations to minimize the effect of fatigue [46] and permit the reconfiguration of the dynamometer to the new test position. The same test order was used in the pre- and post-intervention tests.

2.6. Statistical Analysis

Statistical analysis was performed using IBM-SPSS statistical software (version 29.0.2.0, IBM Corp., Armonk, NY, USA). All data were evaluated for normality using the Shapiro–Wilk test. Outcome variables were determined to be normally distributed, and hence, means and standard deviations (SDs) were used as summary statistics. Potential differences in age and anthropometric characteristics between groups were analyzed using independent *t*-tests, while differences in sex distribution were examined using Fischer's exact test. Potential between group differences in hamstring flexibility, muscle mechanical properties and peak torque generated during isometric and eccentric knee flexion, were assessed using Linear Mixed Models (LMM) within an intention-to-treat (ITT) analysis approach. In each case, group (CG, IG) and time (pre, post) constituted the two-level fixed factors in the model, with participants represented as a random factor. Body Mass Index (BMI), sex, and age were treated as covariates. Significant group × time interactions were investigated using pairwise comparisons along with Bonferroni adjustment for multiple comparisons. The Restricted Maximum Likelihood estimation method was used along with the Satterthwaite approximation for the degrees of freedom, which is preferable for small and unbalanced samples. Effect sizes were estimated using Cohen's *d* with Hedge's correction and classified as small (*d* = 0.20), medium (*d* = 0.50) and large (*d* = 0.80) according to Cohen's classification

system [53]. For pre/post mean differences and effect sizes, 95% confidence intervals (CIs) were used. An α level of ≤ 0.05 was used for all statistical procedures.

3. Results

Twenty recreationally active adults were initially screened for eligibility (Figure 2). Of these, eighteen participants were confirmed eligible for inclusion, successfully completed pre-intervention testing, and were then randomized to either the CG or IG. No adverse events relating to the intervention were reported by participants during this study. However, three participants (one male from the CG and one female/one male from the IG) withdrew after pre-intervention testing due to muscle injury that occurred outside of the study. There was no significant difference in demographic characteristics between groups (Table 2).

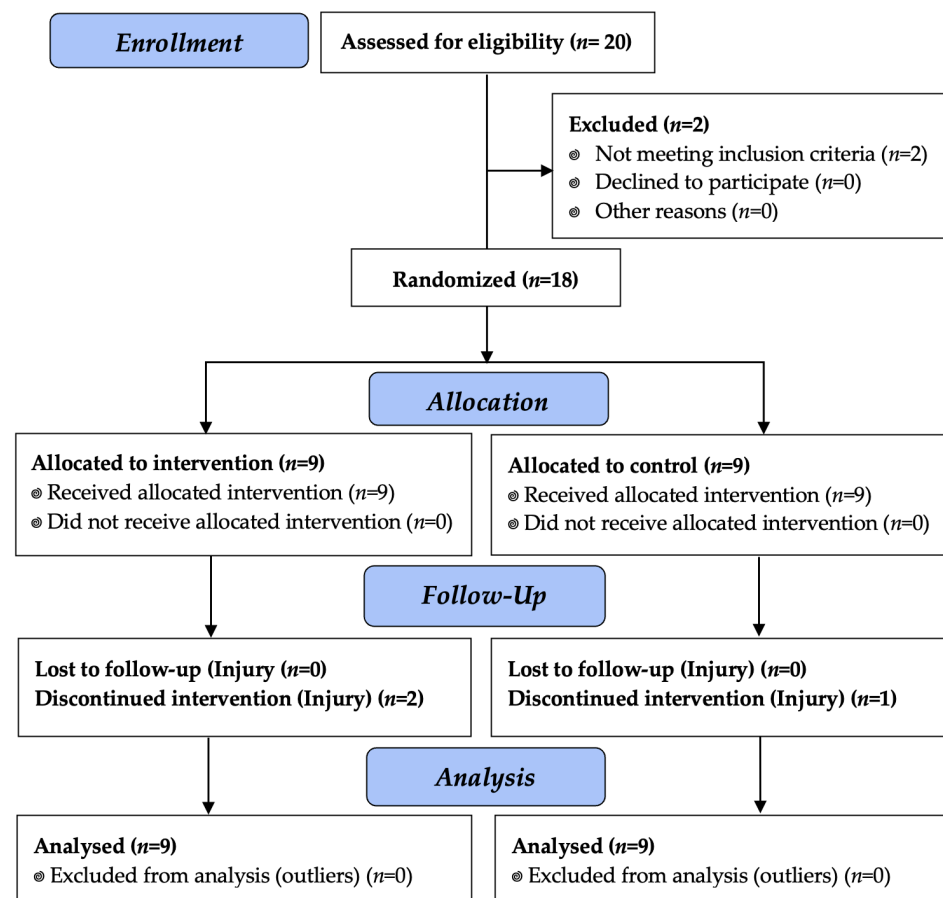


Figure 2. Flow diagram of participant enrollment, allocation, follow-up, and analysis.

Table 2. Mean ($\pm$ SD) characteristics of participants ($n = 18$) in control and intervention groups ¹.

Characteristic	Control Group	Intervention Group
Sample Size	9	9
Sex (Female/Male)	5/4	3/6
Age (years)	24.1 $\pm$ 1.3	23.5 $\pm$ 1.8
Height (cm)	171.9 $\pm$ 2.9	172.9 $\pm$ 3.1
Body Mass (kg)	73.6 $\pm$ 3.4	84.1 $\pm$ 5.2
Body Mass Index (kg m ⁻²)	24.9 $\pm$ 0.9	27.9 $\pm$ 1.5

¹ Note that there were no statistically significant differences between groups ($p > 0.05$).

3.1. Hamstring Flexibility

Figure 3 illustrates the mean hamstring flexibility measured in the CG and IG before and after the 6-week period. Statistical analysis revealed no significant main effect for group ($F_{1,13} = 0.287$, $p = 0.601$). There was, however, a significant main effect for time ($F_{1,13.007} = 13.221$, $p = 0.003$) and significant time $\times$ group interaction ($F_{1,13.007} = 6.615$, $p = 0.023$). Although no significant change was observed in hamstring flexibility in the IG following the NHE (-0.25° [CI: $-0.90, 3.47$], $p = 0.20$, $d = 0.11$ [CI: $-0.93, 0.31$] trivial effect), mean hamstring flexibility increased by 9.5% ($+8^\circ$ [CI: $2.50, 12.50$], $p < 0.05$, $d = 0.43$ [CI: $0.03, 0.83$] small effect) in the CG over the same period.

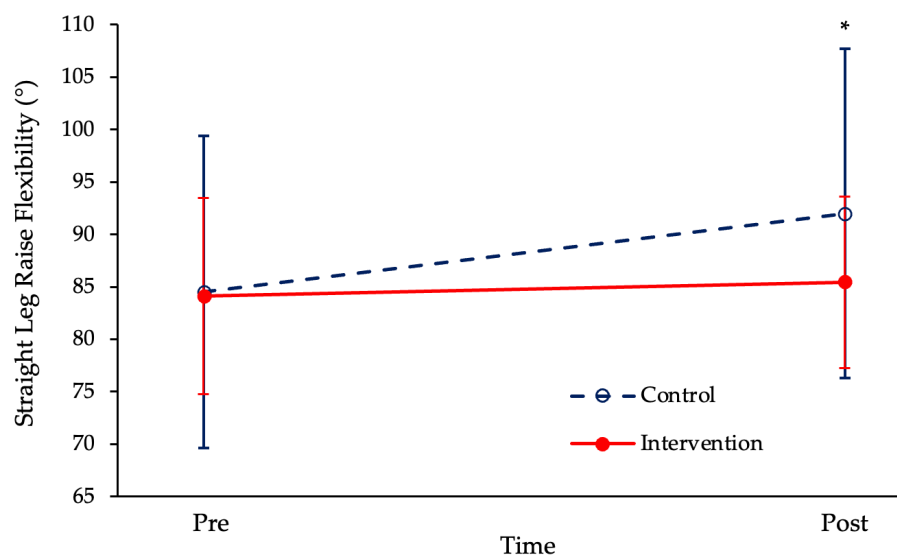


Figure 3. Mean (SD) hamstring flexibility measured in control (dashed line) and intervention (solid line) groups before (pre) and after (post) completion of a progressive, low-volume Nordic hamstring exercise program conducted over 6 weeks. * Indicates a statistically significant group $\times$ time interaction ($p < 0.05$).

3.2. Muscle Mechanical Properties

Figure 4 summarizes the mean tissue properties for each repeated measure in the CG and IG before and after the intervention period. Linear Mixed Methods analysis revealed no significant main effects for group, time, or their interaction for measures of oscillation frequency ($F_{1,13} = 0.016$, $p = 0.902$; $F_{1,13.003} = 0.321$, $p = 0.581$; $F_{1,13.003} = 0.101$, $p = 0.756$), dynamic stiffness ($F_{1,13} = 0.022$, $p = 0.884$; $F_{1,13} = 0.035$, $p = 0.855$; $F_{1,13} = 0.505$, $p = 0.490$), mechanical stress relaxation time ($F_{1,13} = 0.625$, $p = 0.443$; $F_{1,13.007} = 0.174$, $p = 0.684$; $F_{1,13.007} = 0.753$, $p = 0.401$), and logarithmic decrement ($F_{1,13} = 0.623$, $p = 0.444$; $F_{1,13} = 0.001$, $p = 0.980$; $F_{1,13} = 0.842$, $p = 0.376$).

3.3. Isometric and Eccentric Knee Flexor Strength

Peak eccentric and isometric knee flexion torque values for the CG and IG are shown in Table 3. Linear Mixed Methods analysis revealed no significant main effects for group ($F_{1,13} = 1.359$, $p = 0.265$) nor time ($F_{1,13.003} = 0.003$, $p = 0.959$) with respect to eccentric knee torque. A marginal, though not statistically significant, group $\times$ time interaction ($F_{1,13.003} = 4.515$, $p = 0.053$) was also observed, with a small (7%) decrease in peak eccentric torque in the CG (-0.10 N.m.kg $^{-1}$ [CI: $-0.34, 0.09$], $p > 0.05$, $d = -0.36$ [CI: $-1.02, 0.31$], small effect) and an increase (7%) of similar magnitude in the IG following the NHE ($+0.14$ N.m.kg $^{-1}$ [CI: $-0.05, 0.30$], $p > 0.05$, $d = 0.17$ [CI: $-0.09, 0.44$], trivial effect).

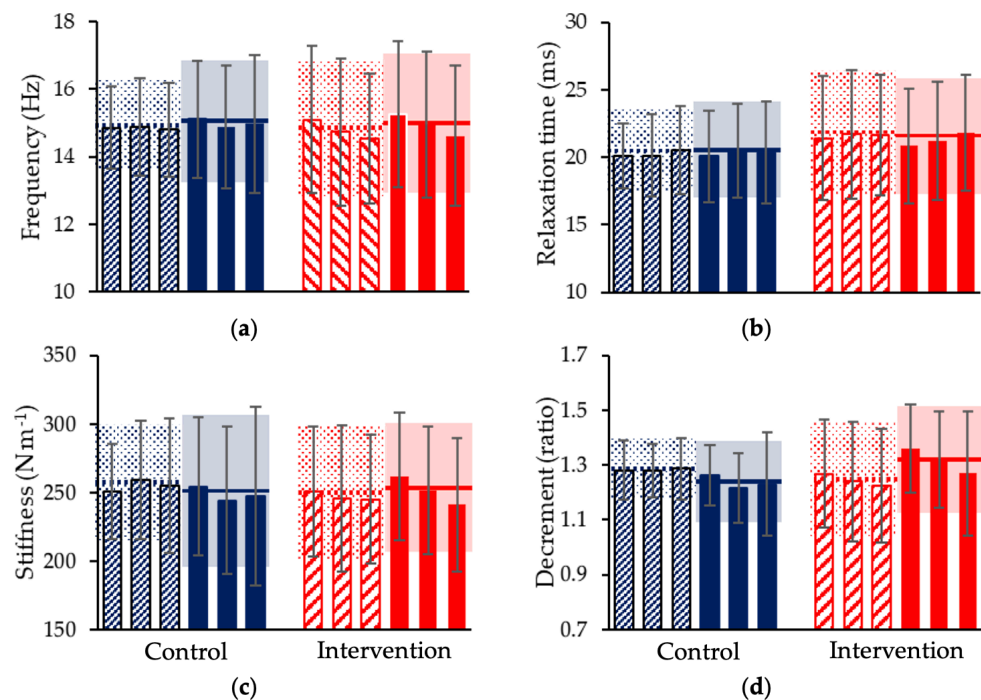


Figure 4. The mean tissue properties for each of three repeated measurements in the control (blue bars) and intervention groups (red bars) before (hatched bars) and after (solid bars) the 6-week NHE period. (a) Natural oscillation frequency. (b) Mechanical stress relaxation time. (c) Dynamic stiffness. (d) Logarithmic decrement. Statistical comparisons were performed on the overall group means (average of triplicate measurements) before (dotted lines) and after (solid lines) the NHE. Shading (dotted and solid) reflects group standard deviations. No statistically significant main effects or interactions between groups were identified for any variable ($p > 0.05$).

Table 3. Peak eccentric and isometric knee flexion torque (normalized to body mass) in control and intervention groups prior to and following 6-week Nordic hamstring exercise program.

Knee Flexor Strength	Control Group		Intervention Group	
	Pre	Post	Pre	Post
Eccentric Peak Torque (Nmkg ⁻¹)	1.84 ± 0.11	1.74 ± 0.06	1.97 ± 0.18	2.11 ± 0.15
Isometric Peak Torque (Nmkg ⁻¹) *	1.56 ± 0.07	1.33 ± 0.06	1.40 ± 0.10	1.47 ± 0.10

* Indicates a statistically significant group $\times$ time interaction ($p < 0.05$).

Similarly, there were no significant main effects for group ($F_{1,13} = 0.016$, $p = 0.902$) or time ($F_{1,13} = 1.149$, $p = 0.303$) for measures of isometric knee torque. However, there was a statistically significant time $\times$ group interaction ($F_{1,13} = 6.765$, $p = 0.022$), which was characterized by a small (+5%) increase in isometric torque in the IG following the intervention period (+0.07 Nmkg⁻¹ [CI: −0.08, 0.23], $p > 0.05$, $d = 0.19$ [CI: −0.22, 0.62], trivial effect) and a larger 12% decrease in isometric torque in the CG (−0.17 Nmkg⁻¹ [CI: −0.34, −0.01], $p < 0.05$, $d = -0.79$ [CI: −1.7, 0.11], medium effect).

4. Discussion

This study assessed the short-term effects of a progressive, low-volume NHE training intervention on eccentric and isometric knee flexor strength, hamstring flexibility and tissue stiffness in young, recreationally active adults. Hamstring flexibility values, as determined by the straight leg raise test, mechanical tissue properties and peak eccentric and isometric knee flexion torques (normalized to body mass) in the current study, were comparable to the broad range of values previously reported in recreationally active adult populations of

similar age [39,51,54–58]. Consistent with our hypothesis, a 6-week, progressive-volume NHE program resulted in a small improvement in isometric and eccentric hamstring strength, as indicated by a 5–7% increase in peak torques in the IG, compared to a 7–12% decrease observed in the CG over the same period. Although generally consistent with previous research [7,12,17], the magnitude of the observed increase in peak isometric and eccentric knee flexor torque in the current study is markedly lower than that typically reported following four to six weeks of NHE training in similarly aged, recreationally active adults (isometric peak +9%; eccentric peak +10% to +15%) [23,29,59,60] and following four- to 12-week NHE programs in both amateur and professional athletes (isometric peak +7%; eccentric peak +7% to +30%) [1,61–63].

Whether the volume and/or progression of Nordic hamstring exercise training programs substantially influence gains in eccentric knee flexor torque remains an area of ongoing research [13]. However, to date, adaptations resulting from NHE training have primarily been assessed over 4–12 weeks [1,23,29,59–63], with many published training interventions either replicating or adopting a derivative of the 10-week protocol described by Mjølsnes et al. [1]. The intervention outlined by Mjølsnes et al. [1] involves rapid progression and high volumes of NHEs, with participants performing more than 700 repetitions across 10 weeks. In contrast, the total volume of NHEs used in the current study was approximately 1.1 to 5.1 times lower than that in most published interventions, with a markedly lower peak rate of exercise progression (2–8 times) (Figure 5). Hence, given that participants had no previous exposure to NHE training [64], it is possible that the relatively small increase observed in peak eccentric and isometric knee flexion torque in our recreationally active cohort reflects the lower volume and/or weekly progression of NHEs. In support of such a concept, Severo-Silveira et al. [65], in a study comparing the effects of a progressive-volume NHE program (236 repetitions over eight weeks) with a constant-volume NHE program (138 repetitions over 8 weeks) in professional Rugby players, identified that only those trained with the progressive, greater-volume program had increased eccentric torque knee flexor torque (+7%). The progressive program and change in flexor torque reported by Severo-Silveira et al. [65] are remarkably similar to those of the current study. It should be recognized, however, that there is also emerging evidence that the low-volume eccentric training of the knee flexors may maintain [66] or even elicit similar strength improvements to high-volume training [67,68], with several systematic reviews concluding, with caution, that NHE volume may have minimal effect on eccentric knee flexor torque [13,14], particularly in programs lasting longer than 6 weeks [12]. It is notable that the current study adopted a 6-week program. Although low-volume NHE programs have also been argued to be more appropriate for recreationally active populations, particularly from an injury prevention perspective [14], further research evaluating the effects of systematic variations in the volume, progression and overall duration of NHE programs on eccentric knee flexor strength and injury rates in recreationally active adults is needed.

According to our second hypothesis, the small increase in knee flexor torque observed following NHE training was not accompanied by either significant improvements in hamstring flexibility or changes in muscle mechanical properties. While these findings are aligned with previous studies, in which NHE programs were found to have no effect on hamstring flexibility [1,23], they are inconsistent with the body of literature, in which changes in muscle architecture and flexibility have typically been reported following eccentric training [8,17,69]. In this context, it is noteworthy that rather than adopting an image-based approach, the current study used myotonometry to estimate the mechanical properties of the biceps femoris, albeit in a direction perpendicular to its primary tensile axis. Classically, myotonometry has been used to measure tissue hardness, with the es-

timates of more complex parameters, such as material stiffness, requiring a number of assumptions including those of homogeneity and a linear, elastic and isotropic response of the tissue to load [70]. It is well known, however, that soft connective tissues are inhomogeneous, anisotropic, and multilayered materials, which are often pre-stressed and demonstrate non-linear, time-dependent behavior with loading [71]. It is perhaps not surprising, therefore, that several studies have questioned the utility of myotonometry to evaluate the biomechanical properties of superficial muscles, such as the hamstrings [72] and their change with pathology [73]. Nonetheless, both *in vitro* and *in vivo* studies have shown that myoton-based measures reflect the underlying tensile force and muscle activity of superficial muscles [74,75], with sufficient sensitivity to detect changes in the tissue with chemical modification [76–78], fatigue [79], and pathology [30,40,80].

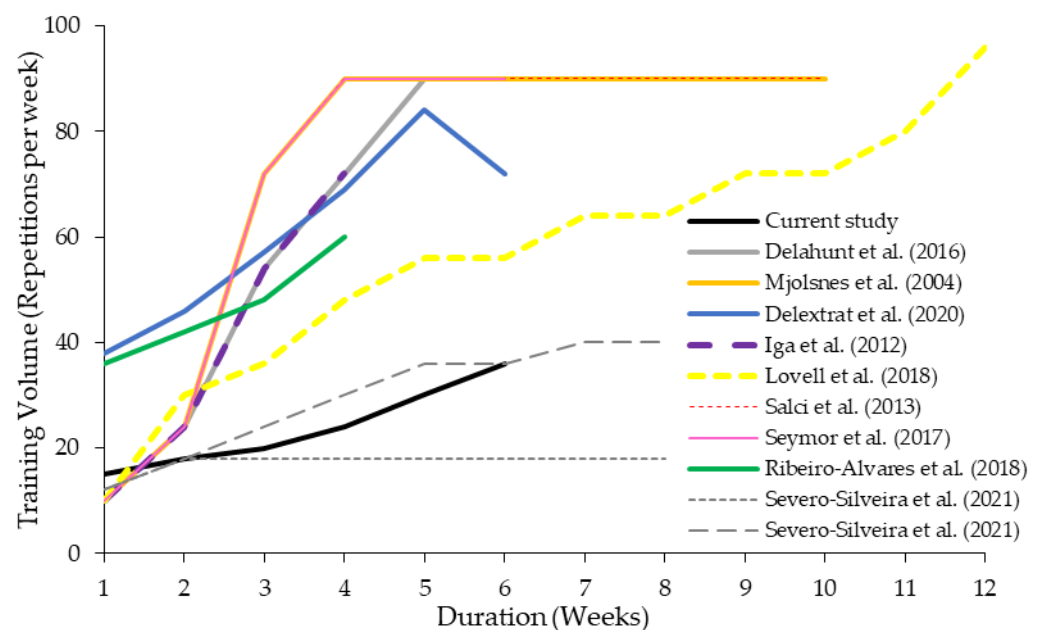


Figure 5. Nordic hamstring exercise repetitions reported as a function of training week used in the current study and typically reported in the literature [1,23,29,59–63,65]. Notably, the current study employed a mid-duration Nordic hamstring exercise program, with a slower progression rate and a lower overall training volume than most of the previous research.

It also seems reasonable to question whether the loading stimulus employed in the current study was sufficient to induce measurable changes in the mechanical properties of collagen-dense soft tissues and, if so, whether such change could appreciably occur within a 6-week study period [81]. In a recent systematic review of 11 studies, Chorp and Zemková [13] concluded that, although both low-volume and high-volume NHE training result in similar improvements in eccentric hamstring strength, high-volume NHE training programs (~2–3 sets of 8–12 repetitions/2–3 times per week) were needed for changes in architecture to occur within hamstring muscle. Likewise, the pooled results of a recent review of six studies (168 participants) drew similar conclusions, citing training volumes in excess of 57 repetitions per week were needed for a period of 6 to 12 weeks for any change in tissue architecture to occur [82], equating to more than double the weekly training volume used in the current study. Moreover, while fascicle length enhancement seems to occur within the first month of NHE training [7], early changes in strength and flexibility with training programs (<3–8 weeks) have been suggested to predominantly reflect neural adaptations including increased muscle excitability [6,29,83] and stretch tolerance [84,85].

Although we found no statistically significant effect of NHE programs on hamstring flexibility with a 6-week NHE program, it is noteworthy that previous studies that have

demonstrated moderate to high improvements in hamstring flexibility over the same period [22,47,86]. It should be noted, however, that in addition to NHEs, these studies have all incorporated some element of long-muscle-length eccentric exercise, such as glider exercises, which involve concomitant hip flexion ($\geq 20^\circ$). Hence, our results, along with those of others who observed no improvement in flexibility with classical (0° hip flexion) NHE training [1,23], raise the intriguing possibility that eccentric hamstring exercises at short muscle length, such as the classical NHE, may not be efficient or sufficient to induce adaptations in flexibility, at least over the short term (4–6 weeks), and may require the support of exercises at long muscle length to evoke a meaningful change in hip range of motion. Nonetheless, we observed that a 6-week, low-volume NHE training program did not adversely affect hamstring flexibility in our cohort of recreationally active adults.

An unexpected finding of our 6-week study was the small increase in the mean hamstring flexibility ($d = 0.43$, small effect), observed in the CG over the study period. This finding was surprising as the CG was explicitly requested to maintain their standard exercise regime and avoid exercises that placed emphasis on the eccentric phase of hamstring contraction. It is possible that such an effect might reflect the larger proportion of females within the CG, as passive hamstring stiffness is typically lower and flexibility higher in females than males [87]. However, we observed no such differences between groups at baseline. Moreover, it is noteworthy that the mean increase in hamstring flexibility observed in the CG was well within the minimal detectable change ($\pm 10^\circ$), and hence measurement error, reported for the single-leg raise test of flexibility [88]. Nonetheless, two participants in the CG had an increase in hip flexion range of motion beyond 10° , while no participant in the IG had a change greater than 5° . Although training diaries support that routine physical activity and exercise regimes in the CG did not change or include hamstring exercises, it was not possible, given the nature of the intervention, to conceal group allocation from participants. Hence, as with all case–control studies involving NHEs, we cannot rule out potential bias arising from the Hawthorne effect. A further caveat to our study was that we did not standardize the routine exercise regimes or levels of physical activity of participants outside of the exercise program. Thus, while this study evaluated the efficacy of the NHE program under real-world conditions, future studies focused on efficacy may wish to either control or include detailed, objective measures of parallel physical activities undertaken by participants during the intervention period. An additional delimitation of our study is that it was statistically powered, *a priori*, to identify only relatively large changes in muscle strength, comparable to those reported in recent meta-analyses evaluating NHE interventions in both athletic ($SMD = 0.96$) and non-athletic populations ($SMD = 1.03$) [14], as well as changes in tissue stiffness reported in injured but fully rehabilitated hamstring muscles ($SMD = 1.23$) [30]. Hence, small- to medium-sized changes in hamstring strength, flexibility or tissue properties may not have been detected. Similarly, this study used non-probability sampling to specifically target healthy, recreationally active adults and was not powered to undertake heterogeneous or subgroup analyses, including those of potential sex-related effects. It is worth mentioning that participant attrition may have affected the power of this study to detect differences, and this constitutes an additional limitation, especially in this study with a relatively small sample size. In addition, although the NHE in the current study was undertaken bilaterally, we evaluated eccentric and isometric knee flexor strength, hamstring flexibility and muscle mechanical properties in only the dominant limb. Based on the findings of the current study, it is recommended that future studies confirm whether changes seen with this progressive, low-volume NHE program occur bilaterally in a variety of populations and in the presence of marked limb asymmetry.

5. Conclusions

Isometric and eccentric hamstring strength can be improved in recreationally active adults using a 6-week, low-volume NHE training program without any meaningful changes in hamstring flexibility or muscle mechanical properties. Importantly, such a program can be implemented with minimal time commitment (approximately 10–12 min per session, twice weekly), making it feasible for recreational populations. This approach may enhance performance while reducing hamstring injury risk during high-intensity activities that heavily load the hamstrings, such as recreational football and other sports involving sprinting and rapid changes in direction.

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Abbreviations

The following abbreviations are used in this manuscript:

CI	Confidence interval
CG	Control group
CV%	Coefficient of variation
IG	Intervention group
NHE	Nordic hamstring exercise
ITT	Intention to treat

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