ORIGINAL SCIENTIFIC PAPER

Acute Effects of Nordic Hamstring Exercise and Romanian Deadlift on Hamstring Shear Modulus and Flexibility

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Abstract
The aim of this study was to investigate the acute effects of Romanian deadlift (RDL) and Nordic hamstring exercise (NHE) on the stiffness and flexibility of hamstring muscles. We hypothesized that a) the RDL would have a greater acute effect on increasing the flexibility, b) the NHE would have a greater acute effect on the increase in stiffness of the biceps femoris (BF) and semitendinosus (ST) in comparison to the semimembranosus (SM), and c) RDL would have a greater acute effect on the increase in stiffness of the SM in comparison to the ST. Twelve young, healthy participants (6 females; 22.8±3.0 years) performed RDL, and 12 participants (8 females; 22.8±3.1 years) performed NHE, with both interventions comprising 5 sets of 10 repetitions. Baseline and post-intervention stiffness was measured using shear–wave elastography, and flexibility using the passive straight leg raise test. There were no significant main effects of time (p=0.744), group (p=0.202), nor the interaction between time and group (p=0.131) for shear modulus. Similarly, no significant main effects of time (p=0.717) and group (p=0.856), nor an interaction between time and group (p=0.444), were observed for flexibility. These findings suggest that neither RDL nor NHE induce immediate measurable changes in hamstring muscle stiffness or flexibility. However, given the small group-specific sample size, the absence of significant effects should be interpreted cautiously and cannot be generalized beyond young, healthy recreationally active individuals.

Keywords: *muscle stiffness, ultrasound elastography, Romanian deadlift, Nordic exercise, hamstring muscles*

Introduction

Eccentric exercises are widely used in strength training and rehabilitation due to their ability to produce high mechanical loading at relatively low metabolic cost, which can promote strength adaptations and, in specific contexts, improvements in muscle–tendon function (LaStayo et al., 2014; Lepley et al., 2017). However, the application of eccentric loading is context-dependent, as high eccentric loads can induce substantial muscle damage and delayed-onset muscle soreness (DOMS), which may be undesirable in some athletic and clinical populations. Eccentric exercise has also been extensively used as a mean of inducing microscopic muscle damage in scientific research, enabling to investigate the physiological processes underlying this damage and the subsequent recovery period (Harris-Love et al., 2021). Microscopic muscle damage induces an inflammatory response, which is associated with a transient reduction in force production capacity and alterations in muscle mechanical properties, including changes in stiffness (Ličen & Kozinc, 2022; Proske & Morgan, 2001). In untrained individuals, this is coupled onset of a distinctive sensation of muscle soreness (Green et al., 2012; Lacourpaille et al., 2017; Proske & Morgan, 2001). While no significant discomfort is typically experienced immediately following exercise, delayed onset muscle soreness (DOMS) and associated increase in muscle stiffness can manifest several hours later, with a peak at approximately 48 hours post-exercise (Green et al., 2012; Lacourpaille et al., 2017; Proske & Morgan, 2001). Recently, ultrasound shear wave elastography (SWE) has been increasingly used to assess muscle stiffness, including in the context of tracking exercise-indiced muscle damage (Ličen & Kozinc, 2022) and neuromuscular fatigue (Maučec & Kozinc, 2026). SWE represents a promising alternative to other methods of exercise-induced muscle injury assessment, such as direct histological examination of muscle samples (biopsy), blood marker analysis and muscle strength measurements (Ličen & Kozinc, 2022). The SWE technique is based on the tracking of the velocity of acoustic shear waves, with faster velocities indicating stiffer tissues (Taljanovic et al., 2017). The shear wave velocity is used to calculate the shear modulus, which is typically expressed in kilopascal (kPa) for muscle and tendon fibres. The shear modulus is a measure of the elastic shear stiffness of the material (Eby et al., 2013; Taljanovic et al., 2017).

Previous research using shear-wave elastography suggests that muscle shear modulus can increase immediately or shortly after eccentric exercise, although findings are not entirely consistent (Ličen & Kozinc, 2022). Importantly, these responses do not appear to be uniform across synergistic muscles. Several studies indicate that some muscles within a functional group may exhibit greater susceptibility to exercise-induced damage than others, potentially resulting in heterogeneous changes in stiffness (Green et al., 2012; Lacourpaille et al., 2017). One proposed explanation is that biarticular muscles may be more prone to damage than monoarticular synergists, possibly due to differences in muscle architecture, strain distribution, and fibre-type composition, including a higher proportion of fast-twitch fibres that are more susceptible to eccentric-induced damage (Green et al., 2012; Lacourpaille et al., 2017; Ličen & Kozinc, 2022). Furthermore, the longer muscle length achieved in eccentric exercise is positively correlated with the amount of muscle damage, which consequently influences changes in shear modulus (Ličen & Kozinc, 2022). These factors are particularly relevant for muscle groups such as the hamstrings, which consists of muscles with distinct architectural and functional characteristics.. Previous research has demonstrated differential activation of individual hamstring muscles during exercises such as the NHE and RDL using electromyography (EMG) (Boyer et al., 2021; Gruhan et al., 2020; Hegyi et al., 2017; Narouei et al., 2018). However, it remains unclear whether these differences in muscle activation are reflected in acute changes in muscle stiffness when assessed using shear-wave elastography.

The acute effects of hamstring-targeted resistance exercise on muscle stiffness and flexibility remain insufficiently understood. For NHE, Cámara-Calmaestra et al. (2024) reported no acute changes in hamstring shear modulus after a single session, but the sample size was small. A particularly relevant study by Kawama et al. (2022) showed that the acute SWE response of the hamstrings depends on exercise characteristics, specifically contraction mode and range of motion. In their study, only eccentric stiff-leg deadlift performed through a wide ROM reduced semimembranosus shear modulus 3 min post-exercise, whereas no significant changes were observed after eccentric exercise with a narrow ROM or concentric exercise with a wide ROM, and no significant changes were found in the biceps femoris long head or semitendinosus. These findings suggest that acute changes in hamstring stiffness are muscle-specific and influenced by the specific exercise stimulus. One possible explanation is that exercise performed at longer muscle lengths may alter passive mechanical behaviour in a manner similar to stretching-induced reductions in stiffness, whereas other forms of resistance exercise may produce no measurable change or even increase stiffness depending on the loading conditions (Fukaya et al., 2020; Kawama et al., 2022; Ličen & Kozinc, 2022). However, despite these important insights, acute responses to commonly used hamstring exercises remain largely unexplored. In particular, no study has directly compared the acute effects of the Nordic hamstring exercise (NHE) and Romanian deadlift (RDL) on the shear modulus and flexibility of individual hamstring muscles.

The aim of this study was to compare the acute effects of Romanian deadlift (RDL) and Nordic hamstring exercise (NHE) on shear modulus of the biceps femoris, semitendinosus, and semimembranosus, and on hamstring flexibility in young, healthy recreationally active adults. The hamstring muscle group was selected due to its high susceptibility to injury and previously reported differences in muscle activation patterns. EMG studies have shown greater activation of the biceps femoris (BF) and semitendinosus (ST) during the NHE compared to the semimembranosus (SM), although findings for the RDL and related exercises are less consistent (Boyer et al., 2021; Gruhan et al., 2020; Hegyi et al., 2017; Martin-Fuentes et al., 2020; Narouei et al., 2018). However, EMG reflects neural activation and does not directly quantify mechanical muscle properties. Therefore, it remains unclear whether these activation differences translate into exercise-specific changes in muscle stiffness, which can be assessed using shear-wave elastography. This study addresses an important gap in the literature by examining whether exercise-specific differences in hamstring activation observed in previous EMG studies are reflected in acute changes in mechanical muscle properties assessed using SWE. We hypothesized that: (a) RDL would induce a greater acute increase in hamstring flexibility than NHE; (b) NHE would induce a greater acute increase in the shear modulus of the BF and ST than of the SM; and (c) RDL would induce a greater acute increase in the shear modulus of the SM than of the ST.

Methods

Participants

Sample size calculation for a three-way mixed ANOVA (effect size (f)=0.25; α error =0.05 and power =0.80) was performed using G*Power 3.1 software (Heinrich Heine University, Düsseldorf, Germany). The effect size (f=0.25; moderate effect, equal to partial eta-squared =0.06) was based on the pool of previous studies generally reporting moderate to high increases in shear modulus after eccentric exercise (Ličen &

Kozinc, 2022). The study included 24 young, healthy recreational athletes (10 males and 14 females) who reported to engage in resistance exercise for at least twice weekly in the past 6 months, with no hamstring or trunk injuries in the six months prior to the study. An additional inclusion criterion was the ability to perform the NHE to at least half range of motion. Basic participant information is presented in the table above. All participants were informed about the purpose, procedures, potential risks, and benefits of the study, and written informed consent was obtained prior to participation. The study was conducted in accordance with the Declaration of Helsinki and was approved by the University of Primorska's Commission for Ethics in Human Subjects Research (approval number: 4264-19-6/23).

Table 1. Basic participant information, split by experimental groups

Variable	Group	Mean	SD	p-value
Age (years)	RDL	22.8	3.0	0.947
	NHE	22.8	3.1	
Body height	RDL	177.3	9.7	0.269
	NHE	171.8	13.4	
Body mass	RDL	69.4	10.6	0.985
	NHE	69.5	11.6	
Romanian dead lift 1RM (kg)	RDL	96.7	25.8	0.331
	NHE	106.7	23.4	

Note. SD – standard deviation; RDL – Romanian dead lift group; NHE – Nordic hamstring exersice group; 1RM – 1-repetition maximum.

Study design

We conducted an experimental study using a parallel design. The study was conducted in April-May 2025 at the kinesiology laboratory of the Faculty of Health Sciences, University of Primorska, Izola. Participation was voluntary and anonymous. Participants were informed in advance about the study's purpose and procedures, which they confirmed by signing an informed consent form. The research methods and interventions employed were non-invasive and harmless. Participants visited the kinesiology laboratory twice. During the first visit, dominant leg determination and familiarization with the exercises were conducted to minimize learning effects and the influence of 1RM testing on baseline stiffness. Following a warm-up, participants' 1RM for the Romanian deadlift was assessed to determine the load for subsequent exercise sessions, and their ability to perform the Nordic hamstring exercise to at least half range was verified. The 1RM was estimated using a submaximal load method and appropriate conversion tables (Baechle & Earle, 2008).

The second visit occurred at least one week after the initial session. Both exercises were performed for 5 sets of 10 repetitions with 2-minute rest intervals between sets. The participants were randomly allocated to their group only at the second visit, by drawing cards from an opaque envelope. The load for the Romanian deadlift was set at 75% of 1RM, using an Olympic barbell (20 kg) with additional weights. For more flexible individuals, a platform was placed under their feet to enable full range of motion. The load for the RDL was set at 75% of 1RM because this represents moderate-to-high resistance-training intensity, while the number of sets and repetitions was matched to the NHE protocol to improve comparability between groups.

Measurement procedures

Muscle stiffness was measured using a Resona 7 ultrasound system (Mindray, Shenzhen, China) with shear wave elastography. The system was set to "SWE" musculoskeletal mode (assuming muscle tissue density of 1000 kg/m³). A medium-sized linear probe (model L11-3U, Midray, Shenzhen, China) was used with water-soluble hypoallergenic ultrasound gel (AquaUltra Basic - Ultragel, Budapest, Hungary). The region of interest was set to 1×1 cm for BF and ST, and 0.5×1 cm for SM. Measurement depth was individually adjusted to capture the middle portion of each muscle and maintained constant across repeated measurements of the same muscle. Probe locations were selected based on Le Sant et al. (2015). Muscle stiffness was expressed as shear modulus in kPa. The final value for each measurement represented the average of eight consecutive measurements, corresponding to the device's maximum storage capacity. For passive leg raise measurements, an inclinometer (EasyAngle, Meloq AB, Stockhom, Sweden) was used following standard joint flexibility assessment protocols.

To ensure ultrasound measurement standardization, several procedures were implemented. The probe was aligned longitudinally with the muscle fascicles using B-mode imaging and maintained perpendicular to the skin surface to avoid anisotropy-related errors. Care was taken to apply minimal and consistent probe pressure, using a generous amount of ultrasound gel to reduce tissue compression. The probe was held manually without additional external fixation, but the examiner was trained to maintain stable positioning throughout all measurements. Measurement sites were marked on the skin using waterproof markers during baseline assessment to ensure consistent probe placement between pre- and post-intervention measurements. Participants were instructed to remain fully relaxed during all measurements, and muscle activity was visually monitored to avoid involuntary contractions. All measurements were performed by the same experienced examiner to minimize inter-operator variability.

During the second visit, baseline measurements were taken after a warm-up and 5-minute rest period. For stiffness measurements, participants were positioned prone on a massage table with extended legs (neutral position). Measurement sites for individual hamstring muscles were marked on the dominant leg with waterproof markers to ensure consistent post-intervention measurement locations. The probe was positioned perpendicular to the muscle with minimal constant pressure. For flexibility measurements, participants were positioned supine, with one examiner performing the passive leg raise while another recorded the inclinometer reading. Post-intervention measurements were conducted following the same protocol after a 5-minute rest period.

Statistical analysis

Data are presented as means ± standard deviations. Normality of data distribution was assessed using the Shapiro–Wilk test and by visual inspection of histograms and Q–Q plots. Intra-class correlation coefficients (ICC; single measures, absolute agreement) were calculated to assess the intra-visit relative reliability of shear modulus measurements across repeated trials at each time point. ICC values <0.50 were interpreted as poor, 0.50–0.75 as moderate, 0.75–0.90 as good, and >0.90 as excellent reliability (Koo & Li, 2016). To complement relative reliability, typical error was also calculated in absolute terms and expressed relative to the mean. Baseline differences between the RDL and NHE groups in participant characteristics and baseline outcome values were assessed using independent-samples t-tests. For shear modulus, a general linear model was applied with time (pre- and post-exercise) and muscle (BF, ST, and SM) as within-participant factors and group (RDL, NHE) as the between-participant factor. For range of motion, a general linear model was applied with time (pre- and post-exercise) as the within-participant factor and group (RDL, NHE) as the between-participant factor. In the case of significant main effects or interactions, post hoc comparisons were performed using t-tests or one-way analyses of variance with Bonferroni correction, as appropriate. Effect sizes for the general linear model were expressed as partial eta squared (ηp^2), with values of 0.01, 0.06, and 0.14 interpreted as small, medium, and large effects, respectively. The threshold for statistical significance was set at $\alpha<0.05$. All analyses were performed using SPSS statistical software (version 25.0, IBM Corp., Armonk, NY, USA).

Results

Twelve participants (six women) were allocated to the RDL group and twelve participants (eight women) to the NHE group. All participants completed the protocol. The groups did not differ in age (p=0.947), body height (p=0.269), or body mass (p=0.985) (Table 1). The mean depth of the region of interest for shear modulus assessment was 1.85±0.32 cm for BF, 1.83±0.30 cm for ST, and 1.78±0.35 cm for SM.

Reliability

All shear modulus measurements demonstrated excellent relative reliability (ICC=0.96–0.99), with the lower bounds of the 95% confidence intervals also within the excellent range (ICC=0.92–0.97).

Typical error ranged from 0.45 to 0.78 kPa across muscles and time points, corresponding to 2.14%–7.39% of the mean values. Detailed reliability results are presented in Supplementary File 1.

Effects of NHE and RDL on hamstrings stiffness

There were no baseline differences between groups for BF (p=0.967), ST (p=0.078), or SM (p=0.899). The analysis revealed no significant three-way interaction between time, muscle, and group (F=0.116, p=0.881). Similarly, no significant two-way interactions were observed for muscle × group (F=0.644, p=0.513), muscle × time (F=0.274, p=0.513), or group × time (F=2.455, p=0.131). There were also no main effects of time (F=0.110, p=0.744) or group (F=1.729, p=0.202). A significant main effect of muscle was found (F=6.639, p=0.004, η^2=0.23). Bonferroni-corrected post hoc analysis indicated that SM exhibited higher shear modulus values compared to BF (p=0.009). No significant differences were observed between ST and BF (p=0.217) or between ST and SM (p=0.188). The results are illustrated in Figure 1.

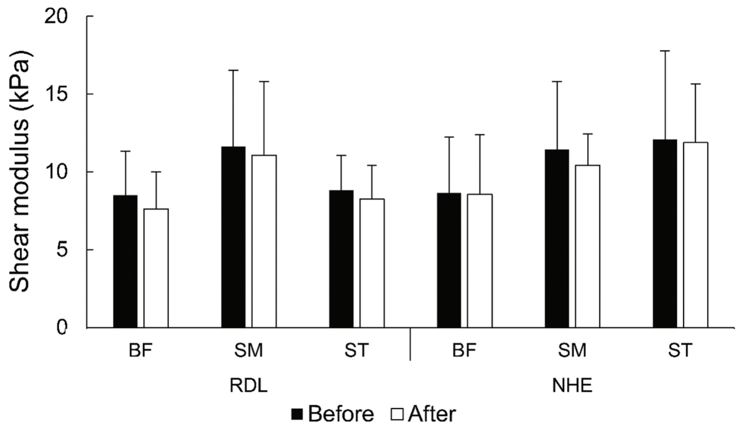

Figure 1. Overview of shear modulus values across time, muscles and groups

Effects of NHE and RDL on range of motion

There was no significant interaction between time and group for range of motion (F=0.607, p=0.444). In addition, no main effects were observed for time (F=0.135, p=0.717) or group (F=0.034, p=0.856). Descriptive statistics and reliability metrics for range of motion are provided in Supplementary File 1.

Discussion

This study examined the immediate effects of RDL and NHE on hamstring shear modulus and flexibility. Neither exercise induced significant time, group, or interaction effects for stiffness or range of motion, although semimembranosus stiffness was higher than biceps femoris across conditions. These findings do not support the initial hypotheses and suggest that these exercise protocols do not produce immediate measurable alterations in hamstring mechanical properties.

Our hypotheses were partly informed by previous EMG studies demonstrating differential activation of hamstring muscles during NHE and deadlift variations. However, in contrast to these findings, the present study did not detect exercise-specific differences in muscle stiffness between individual hamstring muscles. This suggests that differences in neural activation do not necessarily translate into measurable changes in mechanical muscle properties. Existing SWE studies report inconsistent findings regarding acute changes in hamstring stiffness. Kawama et al. (2022) showed that eccentric exercise performed through a wide range of motion can acutely decrease semimembranosus stiffness, while no changes were observed in biceps femoris or semitendinosus. Similarly, no changes in shear modulus following NHE have been reported (Cámara-Calmaestra et al., 2024). In contrast, other studies using high-intensity or isokinetic eccentric protocols have reported increases in stiffness, particularly in the biceps femoris and semitendinosus (Goreau et al., 2022; Magdalena et al., 2024; Voglar et al., 2022). Together, these findings indicate that the direction and magnitude of stiffness changes are highly dependent on the exercise modality and loading conditions.

The absence of significant changes in shear modulus after both exercise protocols is generally consistent with studies showing that acute hamstring stiffness responses are not uniform across exercises, muscles, and assessment time points. For the NHE, our findings align with Cámara-Calmaestra et al. (2024), who also reported no acute changes in hamstring shear modulus following NHE. In contrast, studies using repeated NHE protocols or more controlled high-intensity eccentric contractions have reported increased hamstring stiffness, particularly when the protocol induced substantial fatigue or muscle damage (Goreau et al., 2022; Magdalena et al., 2024; Voglar et al., 2022). Regarding deadlift-type exercises, Kawama et al. (2022) showed that only eccentric stiff-leg deadlift performed through a wide ROM acutely reduced SM shear modulus, whereas narrower ROM or concentric conditions did not alter hamstring stiffness. Therefore, the present findings suggest that the RDL protocol used here, despite involving substantial external load, did not reproduce the stiffness-reducing effect observed after wide-ROM eccentric stiff-leg deadlift. Similarly, the absence of changes in flexibility contrasts with studies showing acute flexibility improvements after stretching or resistance exercise performed through large ROM, but is consistent with the view that resistance exercise does not necessarily acutely increase ROM unless the protocol provides a sufficient lengthening stimulus.

Several mechanistic factors may explain the absence of changes in the present study. First, opposing physiological mechanisms may have contributed to a net neutral effect, as fatigue has been associated with decreased muscle stiffness, whereas exercise-induced muscle damage may increase stiffness (Chalchat et al., 2020; Lacourpaille et al., 2017; Sadeghi et al., 2018; Voglar et al., 2022). Second, the timing of assessment may be critical, as stiffness increases have been reported to occur within 15–60 minutes post-exercise, whereas immediate responses remain less consistent (Dankel & Razzano, 2020). Finally, methodological factors may have influenced sensitivity, as measurements performed in a neutral muscle position and at a single site may not capture region-specific or length-dependent changes in stiffness (Wakahara et al., 2013; Zabaleta-Korta et al., 2020).

Additionally, it is important to consider whether the exercises performed in this study truly induced eccentric contractions in the hamstring muscles. While NHE is traditionally regarded as a high-intensity eccentric exercise, recent research suggests that this may not always be the case. Van Hooren et al. (2022) demonstrated that the behavior of muscle fascicles during NHE may not be purely eccentric, which could influence shear modulus changes. Given that NHE requires simultaneous movement at both the hip and knee joints, it is possible that the specific execution of the exercise in our study did not induce substantial eccentric loading, particularly when compared to isokinetic single-joint eccentric exercises that have been typically used in previous studies to induce muscle damage (Ličen & Kozinc, 2022). If the NHE did not generate sufficient eccentric strain, this could explain the lack of measurable stiffness changes post-exercise. Similarly, the execution of RDL in our study warrants further consideration. Kawama et al. (2022) performed RDL with a low load, which likely allowed participants to perform a controlled eccentric contraction. However, in our study, 5 series of RDL was performed at 75% of 1RM, which may have led to different muscle-tendon unit behavior. At higher loads, the possibility exists that participants were engaging in a quasi-isometric contraction during the lowering phase rather than a true eccentric contraction. This speculation is based on the fact that apparent "eccentric" resistance exercises often involve shortening-stretch contractions at the fascicle level, co-contraction and tension redistribution within the muscle-tendon complex, potentially limiting eccentric strain on muscle fibers (Tecchio et al. 2024).. Since we did not directly measure fascicle length changes or muscle-tendon unit behavior during RDL, we cannot confirm whether true eccentric contractions were occurring. If the RDL protocol used in our study did not sufficiently elongate muscle fibers under tension, it would provide another plausible explanation for the absence of significant changes in shear modulus. The lack of true eccentric contraction could also explain the absence of changes in flexibility, as our study found no significant changes between groups or over time.

This study has several limitations. First, immediate post-exercise measurements may not have captured delayed changes in stiffness and flexibility, as muscle damage effects often peak 24–48 hours post-exercise. Future studies should include multiple follow-up assessments. Second, we measured a single muscle region, potentially overlooking regional variations in stiffness response. Multi-site SWE assessments could provide a more comprehensive picture. Finally, flexibility was assessed using a single test (passive straight leg raise), which may not fully reflect exercise-induced changes. Future research should incorporate additional flexibility measures for a broader evaluation. Another limitation is the absence of a non-exercise control condition, which limits the ability to distinguish exercise-related changes from short-term measurement variability.

Future studies should include larger samples, non-exercise control conditions, and multiple post-exercise follow-up assessments to determine whether stiffness and flexibility responses emerge later after NHE or RDL. Multi-site SWE assessments and measurements at different muscle lengths would help clarify whether these exercises induce region-specific or length-dependent changes in hamstring mechanical properties. In addition, combining SWE with measures of fascicle behaviour, EMG, fatigue, soreness, and strength loss would provide a more comprehensive understanding of whether NHE and RDL produce sufficient eccentric strain or muscle-damaging stimulus to alter hamstring stiffness.

Conclusion

This study investigated the acute effects of RDL and NHE on hamstring stiffness and flexibility, and no significant time or group effects were observed. Only a main effect of muscle was detected, with the SM exhibiting higher stiffness than the BF, independent of exercise or time. These findings suggest that neither exercise induces immediate measurable changes in muscle mechanical properties, contrary to expectations based on prior SWE studies. Future research should explore potential regional variations within individual muscles and consider measuring stiffness at different post-exercise time points. Despite the lack of significant effects, this study provides valuable methodological insights for assessing muscle stiffness and flexibility in sports and rehabilitation setting.

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Conflict of interest
The authors declare that they have no conflict of interest.

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