Hamstring force and stretch during progressively increasing running speeds and the eccentric phase of resistance training exercises commonly used for injury prevention and rehabilitation

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► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/bjsports-2025-110847).

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Accepted 15 January 2026
Published Online First 23 February 2026

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To cite: Breed R, Hulm S, Hickey JT, *et al. Br J Sports Med* 2026;**60**:420–428.

ABSTRACT

Objectives To compare the force and stretch demands experienced by the hamstrings during seven resistance training rehabilitation exercises and progressively increasing running speeds.

Methods A cross-sectional design. Ten male and 10 female active participants performed two trials each of four self-paced gait speeds on a treadmill (walk, and jog, run and sprint at 50%, 75% and 100% of maximum effort, respectively) and two sets of six repetitions each of seven resistance training exercises at a rate of perceived exertion ≥8/10. Data from MRI, electromyography and three-dimensional motion capture were used with musculoskeletal modelling to estimate the muscle forces and musculotendinous unit stretch during each task for the biceps femoris long head (BFlh), semimembranosus (SM) and semitendinosus (ST).

Results The bilateral Romanian deadlift (RDL) produced significantly greater peak force in the BFlh (1.6BW, 95% CI 1.5 to 1.7) and SM (1.9BW, 95% CI 1.8 to 2.1) than any other resistance training or gait task ($p<0.001$). Four resistance training exercises generated peak BFlh forces that were not significantly different ($p\geq0.433$) to maximum speed sprinting (1.0 BW, 95% CI 0.9 to 1.1): unilateral hamstring bridge (1.1 BW, 95% CI 0.9 to 1.2) and the unilateral eccentric hip extension, unilateral eccentric slider and Nordic hamstring exercise (NHE) (all 0.9 BW, 95% CI 0.8 to 1.0). The RDL and unilateral hamstring bridge produced significantly greater peak stretch than any other task for BFlh, SM and ST ($p<0.001$), while the NHE and unilateral eccentric slider produced significantly lower stretch than any other task ($p<0.001$), except the hip thrust for the ST ($p\geq0.143$).

Conclusions The force and stretch demands experienced by the hamstrings during common resistance training exercises ranged from less than walking (eg, hip thrust) to more than sprinting (eg, RDL). However, differences between exercises and running tasks depended on the specific muscle investigated. Our results inform exercise selection strategies for hamstring injury prevention and rehabilitation.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The hamstring muscles produce their peak force and the biceps femoris long head (BFlh) undergoes the greatest stretch of all hamstring muscles during the terminal swing phase of maximum speed sprinting. However, it is unknown what force and stretch the biarticular hamstring muscles are subjected to during various resistance training exercises and progressive running speeds commonly prescribed in hamstring injury prevention and rehabilitation interventions.

WHAT THIS STUDY ADDS

⇒ When performed at a relative intensity of ≥8/10 rate of perceived exertion, the bilateral Romanian deadlift (RDL) and unilateral hamstring bridge exercises produce significantly greater peak force and stretch in the BFlh and semimembranosus than in maximum speed sprinting.

⇒ The hip thrust exercise produces less peak force and stretch in all three hamstring muscles than in walking.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Our findings help guide practitioners to determine what resistance training exercises and running intensities might be most applicable to various stages of the hamstring injury rehabilitation process and select exercises for more targeted injury prevention strategies. For example, the hip thrust exercise could be suited to early rehabilitation stages for strengthening the hamstrings under low stretch, and the RDL could be effective in later stages of rehabilitation or to increase the resistance to BFlh stretch in healthy athletes.

INTRODUCTION

Hamstring strain injury (HSI) is the most common non-contact injury in sports involving high-speed running[1–3] and results in deficits in activation,[4] hamstring strength[5] and high-speed running performance.[6] Exercise selection is central to HSI prevention and rehabilitation, which requires practitioners to understand hamstring musculotendinous tissue loading during various resistance training exercises and common injury scenarios, such as running. The biceps femoris long head (BFlh) is the most frequently injured hamstring muscle[7–9] and has been

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shown to experience high levels of force during rapid lengthening (ie, negative mechanical work) at long lengths during the late swing phase of running.[10] In vitro work suggests that the magnitude of force and stretch experienced by single fibres are strongly related to eccentric contraction induced injury, while lengthening velocity plays a negligible role.[11] Subsequently, resistance training exercises that place force-related and stretch-related demands on hamstrings that reflect those occurring during running may lead to more favourable tissue adaptations and ultimately reduce HSI risk.[12] Quantifying hamstring tissue loads during various resistance training exercises and running could, therefore, support evidence-based exercise selection and progressive overload.

Surface electromyography (EMG) has been the most commonly used method to measure hamstring muscle activity during resistance training exercises.[13 14] However, EMG represents only the neural drive to the muscle rather than estimating the underlying tissue loading. While EMG is related to active force generation within the muscle, this relationship is non-linear and force generation depends on numerous states of the muscle, such as its length and contraction velocity. For example, muscles can generate force passively (ie, without any EMG activity), provided it has been lengthened to a sufficient degree.[15] Musculoskeletal modelling can produce participant-specific estimates of the force and stretch experienced by muscles during movement,[16 17] accounting for the force-length and force-velocity relationships via muscle models.[18] Studies using musculoskeletal modelling for estimating hamstring force and stretch have been conducted in sprinting,[19 20] while investigations of resistance training exercises are limited to one study of just three exercises.[21] Running at progressively increasing speeds forms key progressions towards return to play following HSI;[22] therefore, comparing a greater variety of resistance training exercises and running speeds would provide practitioners with a more comprehensive framework to select and progress hamstring exercises.

This study aimed to evaluate the force and stretch demands experienced by the hamstrings during seven resistance training exercises commonly used for injury prevention and rehabilitation and compare these to the demands experienced at progressively increasing running speeds.

METHODS

Design

Participants completed three sessions: (1) MRI of the hamstrings, (2) familiarisation session and (3) biomechanical data collection. An extended version of the Methods section is found in online supplemental material S1.

Participants

Resistance trained, recreationally active (exercising at least three times per week) adults aged between 18 and 40 years were invited to participate. Participants had to have at least 12 months of experience in resistance training at least twice per week. Exclusion criteria comprised: those with a history of major lower limb injury, surgery or current pain/injury that impacted the ability to perform the tasks; a history of any anterior cruciate ligament injury; significant lower back pain or hamstring injury in the previous 12 months. A sample size of 20 participants was targeted to determine a difference of 1% in peak stretch with 80% power at a significance level of 0.05 (see online supplemental material S2 for further explanation).

Equity, diversity and inclusion statement

Participants recruited for this study could be of any gender, race, ethnicity, religion, culture, socioeconomic status, educational level and background, occupation area of discipline, parental status or geographical location. Of the diversity categories mentioned, the authorship team varied considerably in 9 of 10 areas, with gender being the only commonality.

Patient and public involvement

Patients/public were not involved in the design and conduct of the study, choice of outcome measures or plans for dissemination.

MRI

All participants underwent an MRI in a supine position with a 3.0T scanner (Philips Healthcare, Best, Netherlands), conducted by the same radiographer at one radiology centre (Imaging at Olympic Park, Melbourne, Australia). Automatic muscle and tendon segmentation was performed using validated machine learning technology with a mean volume error of 6.5%.[23]

Progressive running speed and resistance training exercise protocols

Participants were familiarised with running on a non-motorised treadmill and to ensure appropriate exercise techniques. After the treadmill familiarisation, individualised loads for each resistance training exercise were determined based on each participant's rating of perceived exertion (RPE), ensuring an RPE of ≥8/10 for six repetitions. At least 3 days after familiarisation (11±7 days), each participant completed the testing session. The running protocol was performed first at four self-paced speeds, followed by seven resistance training exercises in a randomised order for each participant.

Progressive running speed protocol

Two consecutive trials at each gait speed were performed on a Woodway Curve 3 treadmill (Woodway, Waukesha), which consisted of a self-paced: (1) walk; (2) jog at 50% maximum effort; (3) run at 75% maximum effort and (4) maximum effort sprint. For every gait trial, data were collected for 10 full stride cycles once a consistent speed was observed from the speed-time graph (Pacer Performance System, V.2, Innervations, Perth, Australia).

Resistance training exercises

Exercises consisted of four bilateral tasks (hip thrust, Nordic hamstring exercise (NHE), razor and Romanian deadlift (RDL)) and three unilateral tasks (eccentric hip extension, hamstring bridge and eccentric slider) using the right leg (figure 1). Two sets of six repetitions, with 2 min rest between each set, were completed with 3 min rest between each exercise. Weight increments of 5 kg were used for barbell exercises (hip thrust, RDL), and 1 kg increments using dumbbells or plates were added if required for all other exercises. Participants were instructed to lower 'slowly' during eccentric phases (~3 s) and to perform the concentric component 'fast' if the exercise had one.

Biomechanical data acquisition

During the exercise testing session, participants wore minimal non-reflective exercise clothing and their preferred running shoes. They were instructed not to perform any strenuous activity in the 48 hours before data collection.

Electromyography

Two Mini Wave bipolar surface EMG electrodes (Cometa Wave Plus, Cometa, Bareggio, Italy) were affixed over the biceps femoris (BF) and semitendinosus (ST) mid-bellies of the right

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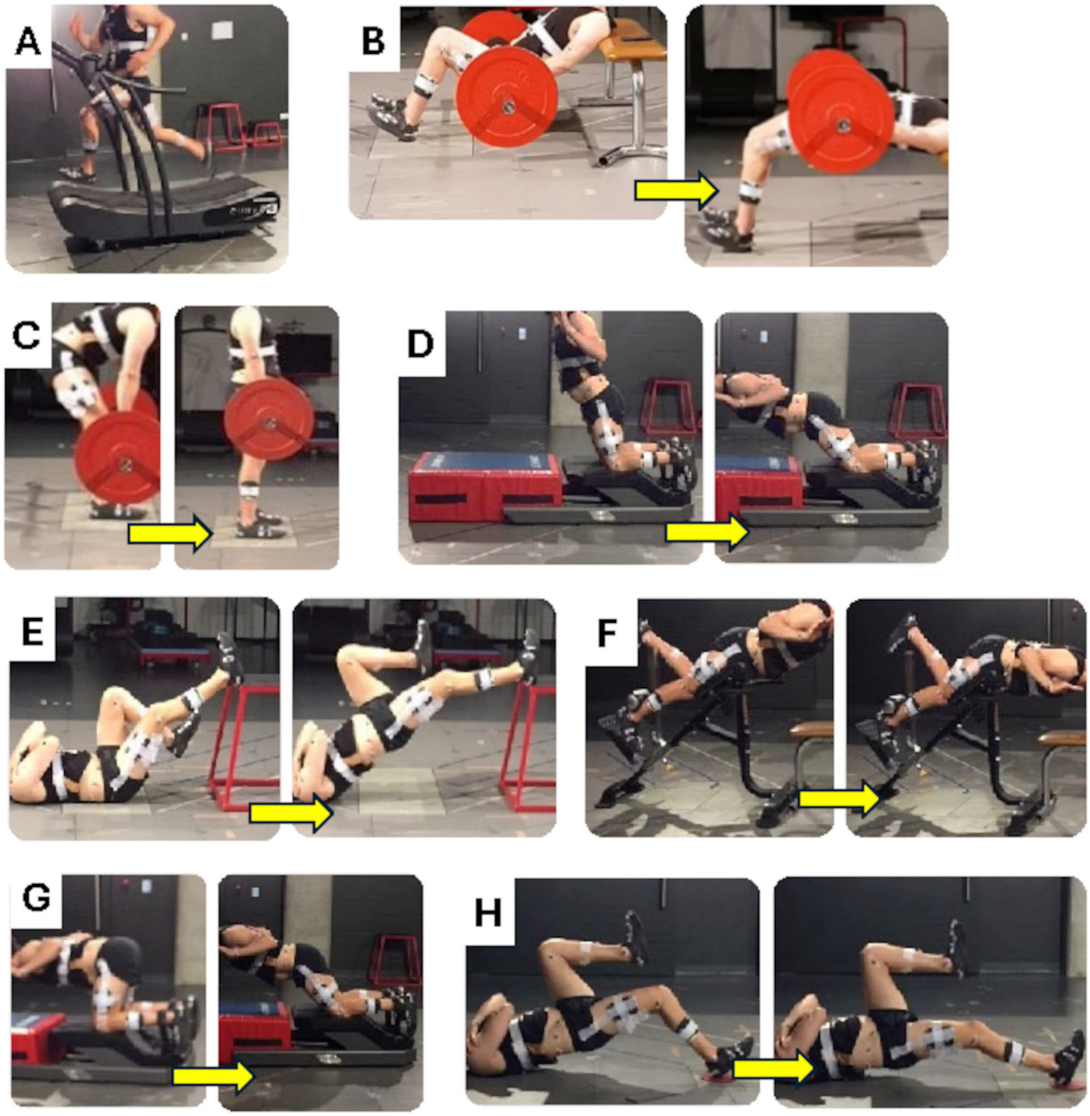

Figure 1 Pictures and brief descriptions of each exercise. (A) Maximal sprinting on Woodway Curve 3 treadmill (Woodway, Waukesha); (B) hip thrust (bilateral) with barbell; (C) Romanian deadlift (bilateral) (RDL) with barbell; (D) Nordic hamstring exercise (bilateral)—eccentric with hands up or across chest if added weight plate; (E) hamstring bridge (unilateral)—with arms across chest and hands on shoulders, 60 cm platform. If weight added, a dumbbell was held along the right thigh using the right arm; (F) eccentric hip extension (unilateral)—with hands up or across chest if dumbbell weight added. Exercise starts at the top, then slowly lowers to the bench. If weight is used, it is placed on the bench at the end of each repetition, then handed to the participant at the top of the exercise by the assistant; (G) razor (bilateral)—eccentric with hands up or across chest if added weight plate; (H) slider (unilateral) – eccentric with arms across chest and hands on shoulders, using gliding disc. If weight was added, a dumbbell was held along the right thigh using the right arm. Both legs were used to bring the body back to the start position.

leg per the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) guidelines.[24] Appropriate electrode placement was confirmed via submaximal contractions and assessment of cross-talk. Maximum voluntary isometric contractions (MVIC) were conducted in a prone position with the knee flexed at ~30°, pushing against a manual resistance. Two maximal-effort contractions (~3 s each) were collected.

Three-dimensional motion capture

Three-dimensional (3D) marker trajectories were collected using a 10-camera motion analysis system (Vicon, Oxford, UK) sampling at 200 Hz. Retroreflective markers were affixed at various locations on the participant's body, per our previous work,[25 26] but adapted to include more markers to account for excess marker-occlusion (online supplemental material S1). A static standing pose was recorded prior to testing (for model scaling) and at least 10 full stride gait cycles and all six repetitions were recorded during each treadmill and resistance training exercise trial, respectively.

Data processing

Where two trials/sets of an exercise or gait task were successfully obtained without data acquisition or analysis issues, the second trial/set was chosen for analysis. Marker data for each trial were digitised using Vicon Nexus V.2.13 software (Vicon, Oxford, UK). Only the middle four repetitions (or gait cycles) were retained for analysis to account for potential artefacts in the beginning and end of the trial. Data were then filtered with a fourth order, zero-lag, Butterworth filter, where marker data were low-pass filtered (cut-off=6 Hz) and EMG data were

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corrected for offset, high-pass filtered (cut-off=20 Hz), full-wave rectified, then low-pass filtered (cut-off=6 Hz) to produce a linear envelope. The filtered EMG signal was normalised to the peak value across all trials (MVIC, gait, resistance training exercises) to produce an excitation signal.

Musculoskeletal modelling

Musculoskeletal modelling was performed in OpenSim V.4.5,[27] using an EMG-driven workflow similar to previously published work.[20 28] A generic, full-body model was scaled to each participant's anthropometry using the 3D marker positions measured during a static standing trial.[29–31] After scaling, the maximum isometric force parameter of each hamstring muscle in the scaled model was updated by dividing each participant's muscle volume (derived from the MRI) by the optimal fibre length (derived from the scaled model) and multiplying by the specific tension constant (60 N/cm^2).[30] Joint angles were then computed via inverse kinematics for the full body during each exercise and the gait tasks using a global optimisation approach.[32] These joint angles were then prescribed in forward dynamic simulations, with the normalised EMG signal used as the excitation input via a prescribed controller. Note that the EMG signal was delayed by 40 ms to account for electromechanical delay.[20] The BF excitation signal was used to drive the BF long head and short head, while the ST excitation signal was used to drive both the ST and semimembranosus (SM) in the musculoskeletal simulations.

Outcome variables

Our analysis of resistance training exercises focused on the eccentric phase of each repetition. For gait tasks, our analysis included the full gait cycle, defined from toe-off to ipsilateral toe-off as per other hamstring mechanics studies.[19] For our statistical analysis, we extracted bodyweight (BW) normalised muscle forces and musculotendinous stretch (%), which expressed the length of the musculotendinous unit (ie, the muscle and tendinous tissue between the origin and insertion) relative to its length in anatomical position. These variables were time normalised to 101 data points (ie, 0% to 100% of the eccentric phase or gait cycle) for visualisation, and peaks were extracted for statistical analysis.

Statistical analysis

Statistical analysis was conducted in the R Statistical Software[33] using the Tidyverse,[34] lme4[35] and emmeans[36] packages. Linear mixed models were applied to determine any differences in task (fixed effect) for each outcome variable, accounting for dependency by modelling participant ID as random intercepts. These models were used for each outcome (force and stretch) and each biarticular hamstring muscle. Tukey's post-hoc pairwise comparisons were used when significant effects for task were found in each model. Assumptions were verified with qqplots and residual plots. Statistical significance was set at $\alpha<0.05$. We report the key findings related to our primary outcome variables (peak muscle force and musculotendinous stretch) and associated p values in the results section. Full statistical results, including marginal mean differences and effect sizes (z-score differences) with 95% CI, are provided in online supplemental material S3.

RESULTS

Study participants

Twenty participants (10 female) took part in the study. Participant characteristics, peak speeds obtained in each gait task, resistance exercise loads and RPE for each exercise are summarised in table 1. Online supplemental material S3 contains additional data not included in our main results, including missing data and further biomechanical data (joint angles, angular velocity, excitation, active and passive BFlh force).

Table 1 Mean, SD and range of group descriptives, exercise loads, gait speeds and MRI-derived maximum isometric force of each hamstring muscle

Variable	Mean	SD	Min	Max
Characteristics				
Age (years)	31	5	22	38
Height (cm)	169	10	149	182
Mass (kg)	67	10	46	88
Load (kg)				
Hamstring bridge	4	4	0	10
Eccentric hip extension	8	5	0	15
Hip thrust	73	24	35	130
Nordic	0	0	0	0
Razor	0	1	0	5
Romanian deadlift	64	16	30	90
Slider	2	3	0	10
Rating of perceived exertion (/10)				
Hamstring bridge	9	1	8	10
Eccentric hip extension	9	1	8	10
Hip thrust	9	0	8	9
Nordic	9	1	8	10
Razor	9	1	8	10
Romanian deadlift	8	0	8	9
Slider	8	1	8	10
Gait speed (m·s^{-1})				
Walk	2.0	0.3	1.4	2.6
Jog	3.2	0.5	2.4	4.2
Run	4.7	0.7	3.9	6.1
Sprint	6.6	0.8	5.1	8.0
Maximum isometric force (N)				
Biceps femoris long head	1331	314	866	2164
Biceps femoris short head	577	216	300	1028
Semimembranosus	1768	414	1079	2440
Semitendinosus	641	190	291	1035

Maximum isometric force was computed by dividing the muscle volume (derived from MRI) by the optimal fibre length (derived from the scaled musculoskeletal model) and multiplying by a specific tension constant 60N.cm^{-2}).

Peak muscle forces

Biceps femoris long head

Time-varying muscle forces are shown in figure 2. The RDL produced significantly greater peak BFlh force (figure 3a) than all other tasks ($p<0.001$). The peak BFlh force during sprinting was not significantly different from the unilateral hamstring bridge, unilateral eccentric hip extension, unilateral eccentric slider or NHE ($p\geq0.433$) but was significantly greater than all other tasks (ie, razor, run, jog, walk, hip thrust; $p\leq0.003$). Running displayed BFlh forces that were not significantly different to the NHE and razor ($p\geq0.152$) but was significantly greater than jogging, walking and the hip thrust ($p<0.001$). The jog, walk and hip thrust were not significantly different from each other ($p\geq0.147$).

Semimembranosus

The RDL produced significantly greater peak SM force (figure 3b) than all other tasks ($p<0.001$). The peak SM force

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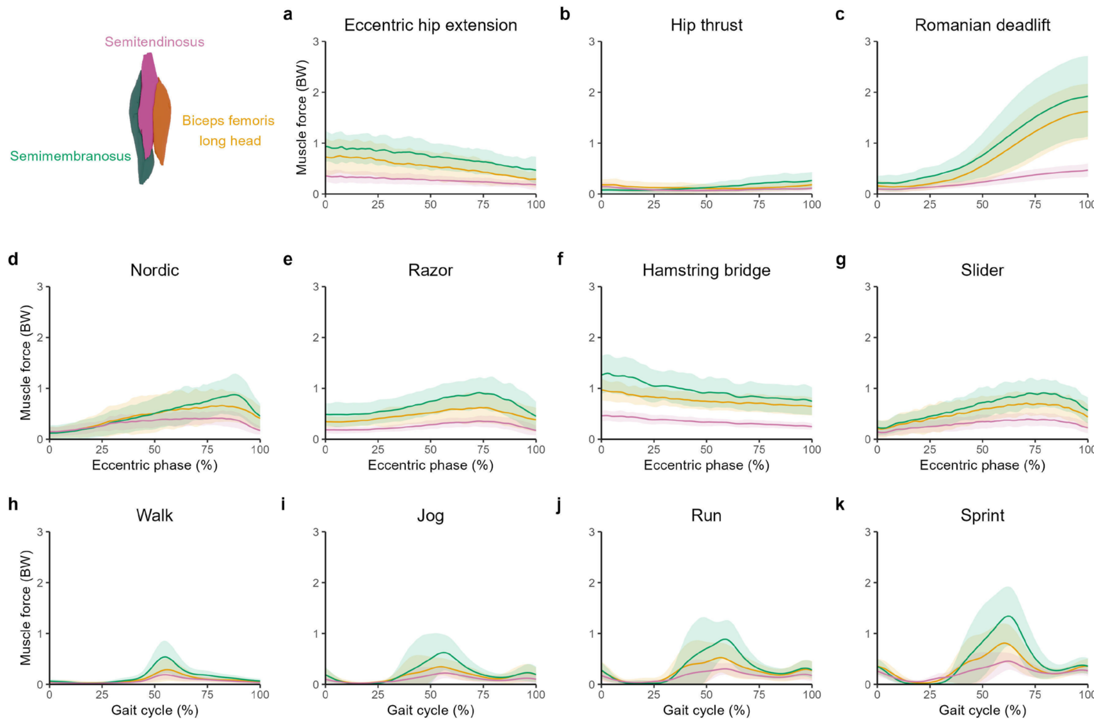

Figure 2 Time-varying hamstring muscle force during exercises and gait. Mean (lines) and SD (shaded area) of bodyweight (BW) normalised muscle forces for the biceps femoris long head (orange), semimembranosus (green) and semitendinosus (pink) across four repetitions of each activity: (a) unilateral eccentric hip extension, (b) hip thrust, (c) Romanian deadlift, (d) Nordic hamstring exercise, (e) razor curl, (f) unilateral hamstring bridge, (g) unilateral eccentric slider, (h) walking at preferred speed, (i) jogging at 50% of max effort, (j) running at 75% of max effort, (k) sprinting at 100% of max effort. For resistance exercises, the x-axis represents the eccentric (lowering) phase, with 0%=start of eccentric phase and 100%=end of eccentric phase. For treadmill exercises, the x-axis represents the stage of the gait cycle for the right leg, with 0%=at toe off and 100%=ipsilateral toe off.

during sprinting was not significantly different to the unilateral hamstring bridge (p=0.994), but both were significantly greater than all other tasks (except the RDL, p≤0.003). Running displayed SM forces that were not significantly different to the unilateral eccentric hip extension, unilateral eccentric slider, razor and NHE (p≥0.995) but was significantly greater than jogging, walking and the hip thrust (p<0.001). The jog and walk were not significantly different from each other (p=0.066), but both were significantly greater than the hip thrust (p≤0.009).

Semitendinosus

Sprinting produced the greatest peak ST force (figure 3c), not significantly different to the NHE, unilateral hamstring bridge or the unilateral eccentric slider (p≥0.886), but significantly greater than all other tasks (p≤0.019). Running displayed ST forces that were not significantly different to the RDL, unilateral eccentric hip extension and the razor (p≥0.348), but was significantly greater than jogging, walking and the hip thrust (p<0.001). The jog and walk were not significantly different

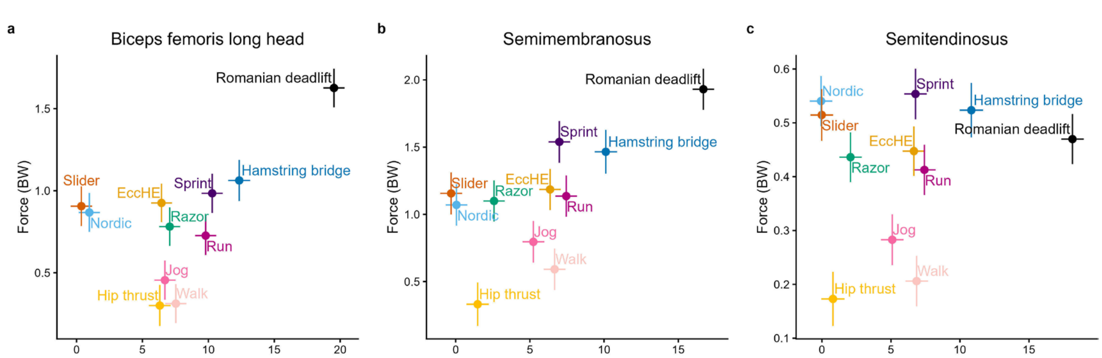

Figure 3 Peak hamstring muscle force and musculotendinous stretch during exercise and gait. Comparison of marginal mean (point) and 95% CI (error bars) of the peak bodyweight (BW) normalised muscle force and musculotendinous unit stretch (%) obtained during the eccentric phase (or full gait cycle) of each exercise (or gait task) for each hamstring muscle: (a) biceps femoris long head, (b) semimembranosus and (c) semitendinosus. Resistance training exercises were performed bilaterally, except the eccentric hip extension (EccHE), hamstring bridge, and eccentric slider. Note that the x-axis and y-axis scales differ between each subplot.

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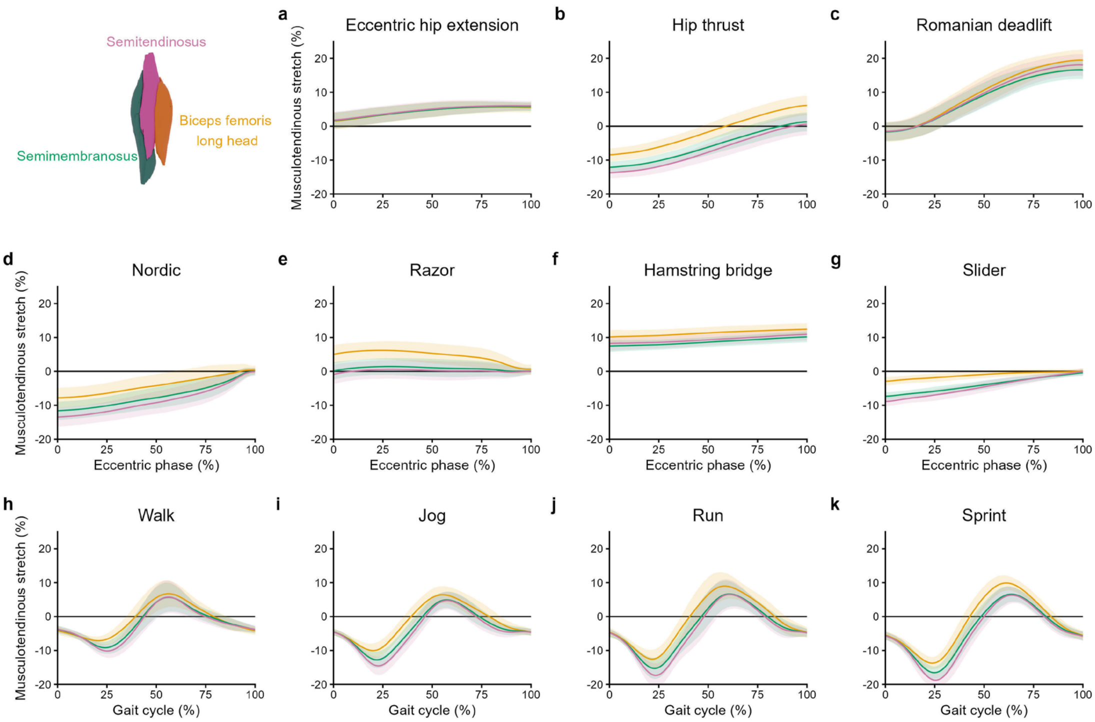

Figure 4 Time-varying hamstring musculotendinous stretch during exercise and gait. Mean (lines) and SD (shaded area) of musculotendinous stretch, normalised as a percentage of the musculotendinous length during static standing, for the biceps femoris long head (BFlh, orange), semimembranosus (SM, green) and semitendinosus (ST, pink) across four repetitions of each activity: (a) unilateral eccentric hip extension, (b) hip thrust, (c) Romanian deadlift, (d) Nordic hamstring exercise, (e) razor curl, (f) unilateral hamstring bridge, (g) unilateral eccentric slider, (h) walking at preferred speed, (i) jogging at 50% of max effort, (j) running at 75% of max effort, (k) sprinting at 100% of max effort. For resistance exercises, the x-axis represents the eccentric (lowering) phase, with 0%=start of eccentric phase and 100%=end of eccentric phase. For treadmill exercises, the x-axis represents the stage of the gait cycle for the right leg, with 0%=at toe off and 100%=ipsilateral toe off.

from each other ($p=0.051$), but the jog was significantly greater than the hip thrust ($p=0.001$).

Peak musculotendinous unit stretch

Biceps femoris long head

Time-varying musculotendinous stretch is shown in figure 4. The RDL produced significantly greater peak BFlh stretch (figure 3a) than all other tasks ($p<0.001$). Other than the RDL, the unilateral hamstring bridge produced significantly greater peak BFlh stretch than all other tasks ($p<0.001$). The peak BFlh stretch during sprinting was not significantly different from running ($p=0.781$), but both the sprint and run were significantly greater than all remaining tasks ($p<0.001$). Walking displayed peak BFlh stretch that was not significantly different to jogging and the razor ($p\geq0.097$), but was significantly greater than all other remaining tasks (ie, unilateral eccentric hip extension, hip thrust, NHE, unilateral eccentric slider; $p\leq0.003$). The razor, jog, unilateral eccentric hip extension and hip thrust were not significantly different from each other ($p\geq0.261$), but all produced significantly greater BFlh stretch than the NHE and unilateral eccentric slider ($p<0.001$).

Semimembranosus

The RDL produced significantly greater peak SM stretch (figure 3b) than all other tasks ($p<0.001$). Other than the RDL, the unilateral hamstring bridge produced significantly greater peak SM stretch than all other tasks ($p<0.001$). Sprinting displayed peak SM stretch that was not significantly different to running, walking and the unilateral eccentric hip extension ($p\geq0.308$), but was significantly greater than other remaining tasks (ie, jog, razor, hip thrust, NHE and unilateral eccentric slider; $p<0.001$). Jogging produced significantly greater peak SM stretch than the razor, hip thrust, NHE and unilateral eccentric slider ($p<0.001$). The NHE and unilateral eccentric slider were not significantly different from each other ($p=0.953$) but produced significantly less SM stretch than any other task ($p<0.001$).

Semitendinosus

The RDL produced significantly greater peak ST stretch (figure 3c) than all other tasks ($p<0.001$). Other than the RDL, the unilateral hamstring bridge produced significantly greater peak ST stretch than all other tasks ($p<0.001$). The peak ST stretch during sprinting was not significantly different from running, walking or the unilateral eccentric hip extension ($p\geq0.439$) but was significantly greater than all remaining tasks (ie, jog, razor, hip thrust, unilateral eccentric slider, NHE; $p<0.001$). Jogging produced significantly greater peak ST stretch than the razor, hip thrust, unilateral eccentric slider and NHE ($p<0.001$). The hip thrust, NHE and unilateral eccentric slider were not significantly different from each other ($p\geq0.143$), but were significantly less that all other tasks ($p\leq0.001$).

DISCUSSION

This is the first study to use an MRI-informed and EMG-driven musculoskeletal modelling approach to quantify force and stretch for each biarticular hamstring muscle during various resistance training exercises and progressively faster running speeds. The RDL elicited the highest peak force in the BFlh and SM and the greatest stretch of any resistance training exercise

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or gait task in all three hamstrings. While significantly less than the RDL, the unilateral hamstring bridge also produced greater stretch than any other task in all hamstrings, while producing forces that were not significantly different to maximal sprinting. The walk and hip thrust elicited the lowest peak forces, and the NHE and unilateral eccentric slider produced the lowest peak stretch in all hamstrings.

Implications for exercise selection in practice

As most rehabilitation protocols use specific gait milestones to assist with return-to-play (RTP) decision-making following a HSI,[9 37] our results in healthy participants may inform exercise selection in sequence from early to late-stage rehabilitation. The hip thrust was the only exercise to have lower peak force and stretch in all three biarticular hamstrings than walking and jogging, thus providing a resistance training exercise option during early stages of rehabilitation, regardless of the muscle injured. It is also relatively simple to progress the load of the hip thrust without change to the stretch. The NHE and unilateral eccentric slider had the least amount of stretch but with higher forces than the hip thrust, so could be suitable as resistance training exercises as participants progress to jogging speeds and above. The razor and unilateral eccentric hip extension may be suitable progressions as participants build to 75% running speed, noting that they provide similar levels of force to the NHE and slider, but under significantly greater stretch.

The RDL and the unilateral hamstring bridge produced similar or higher peak forces to sprinting, but with significantly greater stretch in all three hamstrings. These exercises could provide practitioners with the potential to expose the hamstring muscles to even greater levels of force using different prescription measures, for example, training loads at 90% 1RM or 3-4RM. The RDL and the unilateral hamstring bridge could be effective exercises during later stages of rehabilitation after an athlete has progressed to high-speed running and sprinting activities. Unlike our findings, studies that relied on EMG data only have indicated that sprinting involves the highest muscular activity when compared with various resistance exercises;[12 38 39] however, EMG activity does not directly indicate the force produced.[40] For example, in our study, the RDL had relatively low EMG levels, yet considerably higher passive forces, when compared with other exercises (see online supplemental material S3).

The NHE has commonly been reported to be an effective exercise for reducing HSIs,[41 42] potentially through eccentric strengthening and/or increases in fascicle length, providing a protective effect.[43 44] While the NHE can preferentially recruit the ST,[21] eccentric hamstring exercise under greater stretch might improve BFlh hypertrophy and therefore provide better protection against HSIs.[45–47] In our study, the RDL and unilateral hamstring bridge both produced significantly higher levels of stretch in all three hamstrings than during running and sprinting. This might suggest that these resistance training exercises could be effective alternatives to the NHE for addressing potential HSI risk factors, although prospective randomised controlled trials are needed to verify their efficacy in reducing HSI incidence or burden.

Implications for musculotendinous adaptation

Muscle hypertrophy is widely believed to be driven by mechanical tension (ie, high muscle forces).[48] However, training muscles in a lengthened state has been shown to result in superior hypertrophy (compared with shorter length training) for various muscles,[49] including the hamstrings,[45 46] suggesting that musculotendinous stretch may also inform adaptation. Our results show similar peak BFlh muscle forces in the unilateral eccentric hip extension (0.9BW, 95% CI 0.8 to 1.1BW) compared with the NHE (0.9BW, 95% CI 0.8 to 1.0BW), but with significantly greater peak stretch (6.5%, 95% CI 5.7% to 7.2% vs 1.0%, 95% CI 0.2% to 1.8%). This may help to explain prior findings of greater BFlh hypertrophy from a single-leg 45° hip extension when compared with the NHE.[45] While directly assessing adaptation (eg, morphological changes) to resistance training exercises is ideal to inform practitioners on expected adaptations, our results may provide indirect supporting evidence to inform expected adaptations in the absence of such resource-intensive direct evidence.

Limitations

Since our participants were resistance-trained and recreationally active adults, caution is advised when applying our findings to other populations. Running trials were performed on a non-motorised curved treadmill, which may result in different mechanics to overground running. In addition to the gait trials, each testing session involved participants performing seven resistance exercises (84 repetitions total). We aimed to mitigate any systematic fatigue effects by randomising the resistance training exercise order for each participant. By using subjective RPE to calculate six repetition submaximal loads, individual variations could exist; however, the familiarisation session helped reduce possible variability between participants. Our results could be sensitive to the load used and modifying exercise loads or techniques could potentially change their peak force 'rank order'. For example, exercises that produce forces significantly greater than sprinting could be modified by lowering the load or using only BW. Similarly, range of motion restrictions could be imposed to reduce the stretch within the musculotendinous units, and alternative tempo prescriptions may also modify the loading characteristics of the underlying tissues. Investigating the impact of these modifications on hamstring mechanical loading in exercises is an important area for further research. Due to equipment limitations, not all external forces were accounted for in all exercises; therefore, we could not verify certain assumptions (eg, that the sum of all muscle moments equals the net moment from inverse dynamics). Additionally, the musculoskeletal modelling approach used has other assumptions that cannot be verified, such as the accuracy of the experimental normalised EMG and motion capture data, and the underlying properties of the musculoskeletal model (eg, moment arm—joint angle relationships). However, using an EMG-driven and MRI-informed approach is generally considered best practice and should improve the participant-specific accuracy of the model-derived force estimates.[50] Additionally, our modelling assumptions were held constant across all movements, limiting their ability to confound our primary comparisons between movements, but we suggest caution when directly comparing our force estimates to studies that have used alternative modelling methods.

CONCLUSION

Hamstring mechanical loading during resistance training exercises ranged from less than when walking (eg, hip thrust) and greater than maximal sprinting (eg, RDL), although exact relationships varied depending on the specific muscle. With many rehabilitation programmes using gait tasks such as jogging, running and sprinting as key RTP time milestones, our comparison of common resistance training exercises can assist in the decision-making process when prescribing exercise.

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Acknowledgements Authors would like to acknowledge Mr Declan Carmichael and Miss Kara Price for their assistance with data collection and processing, and the Australian Catholic University Faculty of Health Sciences Project Grant.

Contributors RB: methodology, validation, investigation, data curation, writing—original draft; SH: methodology, validation, investigation, data curation, writing—review and editing; JTH: conceptualisation, methodology, investigation, writing—review and editing, supervision, funding acquisition; RGT: conceptualisation, methodology, writing—review and editing, supervision, funding acquisition; DO: conceptualisation, methodology, writing—review and editing, supervision, funding acquisition; HGB: writing—review and editing, supervision; NM (guarantor): conceptualisation, methodology, software, validation, investigation, data curation, writing—review and editing, visualisation, supervision, funding acquisition.

Funding Project costs were supported by an Australian Catholic University Faculty of Health Sciences Project Grant, and internal funding from the Sports Performance, Recovery, Injury and New Technologies (SPRINT) Research Centre.

Competing interests DO is listed as a co-inventor on a patent (PCT/AU2012/001041.2012), filed by the Queensland University of Technology (QUT), for a field-testing device of eccentric hamstring strength, which is now known commercially as the NordBord. DO has received revenue distributions from QUT based on revenue that QUT has generated through the commercialisation of his intellectual property. DO is a minority shareholder in Vald Performance Pty Ltd, the company responsible for commercialisation of the NordBord. The NordBord was utilised in the current study to assist with the execution of data collection but is not the primary focus of this manuscript. DO has received research funding from Vald Performance, for work unrelated to the current manuscript. DO was previously the Chair of the Vald Performance Research Committee, a role that was unpaid. DO has family members who are minor shareholders and/or employees of Vald Performance.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and was approved by Australian Catholic University Human Research Ethics Committee (number 2018-76H). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer-reviewed.

Data availability statement Data are available upon reasonable request. Non-identifiable data are available from the corresponding author upon reasonable request, subject to the approval of the Australian Catholic University Human Research Ethics Committee.

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REFERENCES

1 Maniar N, Carmichael DS, Hickey JT, *et al*. Incidence and prevalence of hamstring injuries in field-based team sports: a systematic review and meta-analysis of 5952 injuries from over 7 million exposure hours. *Br J Sports Med* 2023;57:109–16.
2 Serner A, Chamari K, Hassanmirzaei B, *et al*. Time-loss injuries and illnesses at the FIFA world cup Qatar 2022. *Sci Med Footb* 2025;9:275–82.
3 Edouard P, Branco P, Alonso JM. Muscle injury is the principal injury type and hamstring muscle injury is the first injury diagnosis during top-level international athletics championships between 2007 and 2015. *Br J Sports Med* 2016;50:619–30.
4 Presland JD, Timmins RG, Maniar N, *et al*. Muscle Activity and Activation in Previously Strain-Injured Lower Limbs: A Systematic Review. *Sports Med* 2021;51:2311–27.
5 Maniar N, Shield AJ, Williams MD, *et al*. Hamstring strength and flexibility after hamstring strain injury: a systematic review and meta-analysis. *Br J Sports Med* 2016;50:909–20.
6 Whiteley R, Massey A, Gabbett T, *et al*. Match High-Speed Running Distances Are Often Suppressed After Return From Hamstring Strain Injury in Professional Footballers. *Sports Health: A Multidisciplinary Approach* 2021;13:290–5.
7 Kenneally-Dabrowski C, Serpell BG, Spratford W, *et al*. A retrospective analysis of hamstring injuries in elite rugby athletes: More severe injuries are likely to occur at the distal myofascial junction. *Phys Ther Sport* 2019;38:192–8.
8 Roe M, Murphy JC, Gissane C, *et al*. Hamstring injuries in elite Gaelic football: an 8-year investigation to identify injury rates, time-loss patterns and players at increased risk. *Br J Sports Med* 2018;52:982–8.
9 Breed R, Opar D, Maniar N, *et al*. Epidemiology of Hamstring Strain Injuries in Elite Male Australian Football Players: An Analysis of 773 Injuries Over 7 Seasons. *JOSPT Open* 2024;2:289–96.
10 Schache AG, Dorn TW, Blanch PD, *et al*. Mechanics of the human hamstring muscles during sprinting. *Med Sci Sports Exerc* 2012;44:647–58.
11 Stauber WT. Factors involved in strain-induced injury in skeletal muscles and outcomes of prolonged exposures. *J Electromyogr Kinesiol* 2004;14:61–70.
12 Prince C, Morin J-B, Mendiguchia J, *et al*. Sprint Specificity of Isolated Hamstring-Strengthening Exercises in Terms of Muscle Activity and Force Production. *Front Sports Act Living* 2020;2:609636.
13 Bourne MN, Williams MD, Opar DA, *et al*. Impact of exercise selection on hamstring muscle activation. *Br J Sports Med* 2017;51:1021–8.
14 Hegyi A, Csala D, Péter A, *et al*. High-density electromyography activity in various hamstring exercises. *Scand J Med Sci Sports* 2019;29:34–43.
15 MacIntosh BR. Recent developments in understanding the length dependence of contractile response of skeletal muscle. *Eur J Appl Physiol* 2017;117:1059–71.
16 Sylvester AD, Lautzenheiser SG, Kramer PA. A review of musculoskeletal modelling of human locomotion. *Interface Focus* 2021;11:20200060.
17 Luis I, Afschrift M, De Groote F, *et al*. Evaluation of musculoskeletal models, scaling methods, and performance criteria for estimating muscle excitations and fiber lengths across walking speeds. *Front Bioeng Biotechnol* 2022;10:1002731.
18 Millard M, Uchida T, Seth A, *et al*. Flexing computational muscle: modeling and simulation of musculotendon dynamics. *J Biomech Eng* 2013;135:021005.
19 Schache AG, Dorn TW, Wrigley TV, *et al*. Stretch and activation of the human biarticular hamstrings across a range of running speeds. *Eur J Appl Physiol* 2013;113:2813–28.
20 Arnold EM, Hamner SR, Seth A, *et al*. How muscle fiber lengths and velocities affect muscle force generation as humans walk and run at different speeds. *J Exp Biol* 2013;216:2150–60.
21 Van Hooren B, Vanwanseele B, van Rossom S, *et al*. Muscle forces and fascicle behavior during three hamstring exercises. *Scand J Med Sci Sports* 2022;32:997–1012.
22 Zambaldi M, Beasley I, Rushton A. Return to play criteria after hamstring muscle injury in professional football: a Delphi consensus study. *Br J Sports Med* 2017;51:1221–6.
23 Ni R, Meyer CH, Blemker SS, *et al*. Automatic segmentation of all lower limb muscles from high-resolution magnetic resonance imaging using a cascaded three-dimensional deep convolutional neural network. *J Med Imag* 2019;6:1.
24 Opar DA, Williams MD, Timmins RG, *et al*. Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. *J Electromyogr Kinesiol* 2013;23:696–703.
25 Maniar N, Schache AG, Cole MH, *et al*. Lower-limb muscle function during sidestep cutting. *J Biomech* 2019;82:186–92.
26 Maniar N, Schache AG, Sritharan P, *et al*. Non-knee-spanning muscles contribute to tibiofemoral shear as well as valgus and rotational joint reaction moments during unanticipated sidestep cutting. *Sci Rep* 2018;8:2501.
27 Delp SL, Anderson FC, Arnold AS, *et al*. OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans Biomed Eng* 2007;54:1940–50.
28 Arnold EM, Delp SL. Fibre operating lengths of human lower limb muscles during walking. *Philos Trans R Soc Lond B Biol Sci* 2011;366:1530–9.
29 Lai AKM, Arnold AS, Wakeling JM. Why are Antagonist Muscles Co-activated in My Simulation? A Musculoskeletal Model for Analysing Human Locomotor Tasks. *Ann Biomed Eng* 2017;45:2762–74.
30 Rajagopal A, Dembia CL, DeMers MS, *et al*. Full-Body Musculoskeletal Model for Muscle-Driven Simulation of Human Gait. *IEEE Trans Biomed Eng* 2016;63:2068–79.
31 Uhlrich SD, Jackson RW, Seth A, *et al*. Muscle coordination retraining inspired by musculoskeletal simulations reduces knee contact force. *Sci Rep* 2022;12:9842.
32 Lu TW, O'Connor JJ. Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. *J Biomech* 1999;32:129–34.
33 Team RC. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing.2025. Available: https://www.R-project.org
34 Wickham H, Averick M, Bryan J, *et al*. Welcome to the Tidyverse. *JOSS* 2019;4:1686.
35 Bates D, Mächler M, Bolker B, *et al*. Fitting linear mixed-effects models using lme4. *J Stat Softw* 2015;67:1–48.
36 Lenth R. Emmeans: estimated marginal means, aka least-squares means (v1.11.1).
37 Dunlop G, Ardern CL, Andersen TE, *et al*. Return-to-Play Practices Following Hamstring Injury: A Worldwide Survey of 131 Premier League Football Teams. *Sports Med* 2020;50:829–40.
38 van den Tillaar R, Solheim JAB, Bencke J. COMPARISON OF HAMSTRING MUSCLE ACTIVATION DURING HIGH-SPEED RUNNING AND VARIOUS HAMSTRING STRENGTHENING EXERCISES. *Int J Sports Phys Ther* 2017;12:718–27.

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39 Jorge A, Lichtenstein E, Faude O, *et al*. Muscle Activity and Kinematics During Three Hamstring Strengthening Exercises Compared to Sprinting: A Cross-Sectional Study. *Int J Sports Phys Ther* 2024;19:569–80.
40 Collings TJ, Bourne MN, Barrett RS, *et al*. Reconsidering Exercise Selection with EMG: Poor Agreement between Ranking Hip Exercises with Gluteal EMG and Muscle Force. *Med Sci Sports Exerc* 2025;57:1829–37.
41 Al Attar WSA, Soomro N, Sinclair PJ, *et al*. Effect of Injury Prevention Programs that Include the Nordic Hamstring Exercise on Hamstring Injury Rates in Soccer Players: A Systematic Review and Meta-Analysis. *Sports Med* 2017;47:907–16.
42 van Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. *Br J Sports Med* 2019;53:1362–70.
43 Crawford SK, Sandberg C, Vlisides J, *et al*. Hamstrings Muscle Architecture and Morphology Following 6 wk of an Eccentrically Biased Romanian Deadlift or Nordic Hamstring Exercise Intervention. *Med Sci Sports Exerc* 2025;57:1799–809.
44 Alonso-Fernandez D, Docampo-Blanco P, Martinez-Fernandez J. Changes in muscle architecture of biceps femoris induced by eccentric strength training with nordic hamstring exercise. *Scand J Med Sci Sports* 2018;28:88–94.
45 Bourne MN, Duhig SJ, Timmins RG, *et al*. Impact of the Nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. *Br J Sports Med* 2017;51:469–77.
46 Maeo S, Balshaw TG, Nin DZ, *et al*. Hamstrings Hypertrophy Is Specific to the Training Exercise: Nordic Hamstring versus Lengthened State Eccentric Training. *Med Sci Sports Exerc* 2024;56:1893–905.
47 Lazarczuk SL, Collings TJ, Hams AH, *et al*. Hamstring Muscle-Tendon Geometric Adaptations to Resistance Training Using the Hip Extension and Nordic Hamstring Exercises. *Scand J Med Sci Sports* 2024;34:e14728.
48 Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. *J Strength Cond Res* 2010;24:2857–72.
49 Wolf M, Korakakis PA, Roberts MD, *et al*. Does longer-muscle length resistance training cause greater longitudinal growth in humans? A systematic review. *Sports Medicine and Health Science* 2025.
50 Akhundov R, Saxby DJ, Diamond LE, *et al*. Is subject-specific musculoskeletal modelling worth the extra effort or is generic modelling worth the shortcut? *PLoS One* 2022;17:e0262936.

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