Received: 14 March 2020 | Revised: 7 July 2020 | Accepted: 10 July 2020

DOI: 10.1111/sms.13770

ORIGINAL ARTICLE

WILEY

Effects of eccentric training at long-muscle length on architectural and functional characteristics of the hamstrings

Jan Marušič[1] | Rok Vatovec[1] | Goran Marković[2,3] | Nejc Šarabon[1,4]

[1]Faculty of Health Sciences, University of Primorska, Izola, Slovenia

[2]Faculty of Kinesiology, University of Zagreb, Zagreb, Croatia

[3]Motus Melior Ltd., Zagreb, Croatia

[4]Laboratory for Motor Control and Motor Behavior, S2P, Science to practice, Ltd., Ljubljana, Slovenia

Correspondence
Nejc Šarabon, Faculty of Health Sciences, University of Primorska, Polje 42, SI-6310 Izola, Slovenia.
Email: nejc.sarabon@fvz.upr.si

Funding information
Javna Agencija za Raziskovalno Dejavnost RS, Grant/Award Number: L5-1845 and P5-0147 (B)

Hamstring strain injuries during sprinting or stretching frequently occur at long-muscle length. Yet, previous research has mainly focused on studying the effectiveness of eccentric hamstring strengthening at shorter muscle length on hamstring performance, morphology, and hamstring strain injury risk factors. Here, we evaluated the effects of 6-week eccentric hamstring training at long-muscle length on functional and architectural characteristics of the hamstrings. Healthy and injury-free participants (n = 40; age 23.7 ± 2.5 years) were randomly assigned to control or intervention group. Training intervention consisted of 12 sessions with two eccentric hamstring exercises in a lengthened position. Outcome measures included isokinetic and isometric knee flexion peak torque, Nordic hamstring exercise peak torque, voluntary activation level, and countermovement jump performance. Ultrasonography was used to determine muscle thickness, pennation angle, and fascicle length of biceps femoris long head (BFlh). A significant time × group interaction effect was observed for all measured parameters except countermovement jump performance and muscle thickness. The training intervention resulted in increased concentric and eccentric knee flexion peak torque at 60°/s ($d = 0.55$-0.62, $P = .02$ and $.03$) and concentric peak torque at 180°/s ($d = 0.99$, $P = .001$), increased isometric knee flexion peak torque ($d = 0.73$, $P = .008$) and Nordic hamstring exercise peak torque ($d = 1.19$, $P < .001$), increased voluntary activation level ($d = 1.29$, $P < .001$), decreased pennation angle ($d = 1.31$, $P < .001$), and increased fascicle length ($d = 1.12$, $P < .001$) of BFlh. These results provide evidence that short-term eccentric hamstring strengthening at long-muscle length can have significant favorable effects on various architectural and functional characteristics of the hamstrings.

KEYWORDS
biceps femoris, fascicle length, knee flexion torque, pennation angle, strength

1 | INTRODUCTION

Hamstring strain injury (HSI) is the most common non-contact muscle injury in high-speed running sports, such as soccer, track and field, rugby, American football, and Australian football, with biceps femoris long head (BFlh) being predominantly affected (for review, see Erickson and Sherry).[1] In addition, studies report a rate of 16%-23% for HSI recurrence in some of these sports, while previous HSI present the greatest risk factor for the occurrence of the HSI.[1]

The majority of HSIs occur during maximal or near-maximal sprinting, particularly during the late swing phase when muscle-tendon units (MTU) of all biarticular hamstring muscles experience peak strains and peak forces and absorb the greatest amount of energy (for review, see Maniar et al[2]). Since muscle strain injuries seem to be related to the magnitude of fiber strain and the amount of energy absorbed during active lengthening,[3,4] training strategies that would enhance the capacity of hamstring muscles to tolerate active strain and to absorb energy during eccentric loading could be particularly effective in reducing the risk of HSIs.

One such training strategy is eccentric training, with a typical representative exercise being the Nordic hamstring exercise (NHE).[5] Indeed, programs that include the NHE induce favorable changes in established modifiable HSI risk factors (eg, eccentric knee flexor strength, BFlh fascicle length[6]) and reduce HSIs by up to 51%.[5] However, it should be noted that the NHE is a knee-dominant movement performed with neutral hip position (0° hip flexion) and with limited knee joint range of motion due to participants' lack of eccentric knee flexor strength. As a result, NHE (a) does not enable eccentric strengthening at hamstring lengths that are similar to the lengths achieved in the late swing phase of the sprinting and (b) has limited potential in eliciting high strains and high negative work in biarticular hamstring MTUs.

These potential disadvantages could be solved with maintaining increased hip flexion during the NHE to enable strengthening in a lengthened position, as shown by Sarabon et al[7] Furthermore, in order to activate all biarticular hamstring muscles at lengths experienced during sprinting, a more holistic approach to hamstring training would require inclusion of both knee and hip-dominant exercises at long-muscle length.[8] However, such an approach to hamstring strengthening has been generally neglected in the scientific literature. Limited data suggest that eccentric strengthening in a lengthened position is effective in hamstring rehabilitation.[9,10] Recently, Guex et al[11] have reported positive effects of short-term eccentric knee flexion training performed in a lengthened position on the isokinetic device on architectural and functional characteristics of the hamstrings. Yet, this intervention lasted only 3 weeks, did not include hip-dominant eccentric exercise at long-muscle length, and has utilized expensive and inaccessible isokinetic training equipment.

Contrary to isokinetic device, more accessible, feasible, and less time-consuming exercises like the modified NHE[7] and the glider[9] could present a more practical approach for eccentric hamstring training in a lengthened position, while respecting its function as both knee flexor and hip extensor. Sarabon et al[7] have recently demonstrated that, compared with the traditional NHE, the modified NHE with hips flexed at 50-75° allowed performing greater total ranges of motion with higher knee and hip joint torques. These conditions are likely to increase both the strain and the energy absorbed in MTUs of hamstring muscles. Contrary to bilateral, knee-dominant nature of the modified NHE, the glider is unilateral, hip-dominant eccentric exercise that allows maximal elongation of the hamstring muscles. During performance of the glider, hip flexion reaches angle similar to the one observed during the late swing phase of sprinting, with similar maximal contraction levels of medial and lateral biarticular hamstring muscles.[12]

Given the limited knowledge about the neuromuscular adaptations of hamstring muscles to eccentric training in a lengthened position when combining knee and hip-dominant exercises, the main purpose of the present study was to assess the effects of the 6-week eccentric hamstrings training using the modified NHE and the glider exercise on architectural and functional characteristics of the hamstring muscles. Based on results of previous research,[11,13-15] we hypothesized that the aforementioned eccentric training in a lengthened position would (a) increase fascicle length of the BFlh, (b) increase hamstrings strength, voluntary activation level and vertical jump performance, and (c) shift the peak of the knee flexor torque-angle curve in the direction of longer hamstrings lengths.

2 | MATERIALS AND METHODS

2.1 | Participants

Forty healthy volunteers were included at the beginning of this study and randomized to either intervention or control group. Both groups were measured pre- and post-intervention. Thirty-four of them successfully completed the study. Their demographic and physical characteristics are shown in Table 1. Minimal sample size of 16 participants in each of the two groups was determined a priori for 80% statistical power, an alpha error of 0.05 and an effect size of 0.75. This effect size was selected as recent meta-analytical review revealed that the eccentric hamstring strengthening results in large increases (effect sizes >1.0) in eccentric hamstring strength and BFlh fascicle length.[16] All participants self-reported as being recreationally active (>3 hours of physical activity per week). The inclusion criteria were the ability to descend actively to at least 50% of the full range of motion during the standard NHE. The exclusion

TABLE 1 Descriptive statistics of the study participants (mean ± SD)

Group	Male/female	Age [y]	Height [m]	Mass [kg]	BMI [kg/m^2]	Body fat [%]	Muscle mass [%]
Intervention	12/6	24.2 ± 2.1	1.77 ± 0.09	73.0 ± 14.3	23.0 ± 3.2	15.1 ± 5.3	80.7 ± 5.1
Control	12/4	23.0 ± 2.8	1.79 ± 0.07	75.1 ± 15.1	23.2 ± 3.5	16.3 ± 6.7	79.6 ± 6.4

criteria were neural, muscular, skeletal, or connective tissue injuries during the last 12 months in the area of the back, hips, and/or legs. All participants were informed about the purpose and content of the study and gave written informed consent prior to participation. The study was approved by the National Medical Ethics Committee (0120-690/2017/8) and conducted according to the Declaration of Helsinki.

2.2 | Intervention training program

The control group was instructed not to change their recreational habits. The intervention training program consisted of two eccentric hamstring exercises in a lengthened position: the modified NHE (Figure 1, starting position A, final position B) and the glider (Figure 1, starting position C, final position D). The modified NHE was performed bilaterally in a custom-designed device with adjustable slope of the lower leg support (S2P Ltd., Science to practice). The NHE device and the modified NHE variation were previously described by Sarabon et al,[7] who showed that adding hip flexion during the NHE can lengthen hamstrings at the time of peak knee and hip torque and peak hamstring electromyographic activity. Participants were instructed to maintain 75° of hip flexion during each repetition of the NHE. Hip flexion angle was constantly checked by the supervisor using a goniometer on each training session. The glider exercise is a part of Askling L-protocol for hamstring rehabilitation.[9] It is a unilateral, hip-dominant exercise, in which most of the bodyweight is on the front leg while the other leg is slowly sliding backward; hamstrings of the front leg are thus loaded eccentrically. Participants were instructed to perform both exercises in a controlled manner (each repetition lasted 3-5 seconds) with proper form and without any pain to the maximum possible range of motion. Both legs were trained in the glider exercise. Progression of both exercises was achieved by either adding extra weight or number of repetitions. Extra weight ranged (depending on the individual`s strength) from 5-10 kg during the modified NHE (held in both hands in front of chest) and 8-20 kg during the glider exercise (held in non-supported hand). Weight was chosen based on the individual's rate of perceived exertion value on their last repetition (if it was below 8, the weight was increased). Total number of sets and repetitions for each exercise within training sessions was as follows:

- week 1:2 sets × 5 repetitions;
- week 2:2 sets × 6 repetitions;
- week 3:3 sets × 6 repetitions;
- weeks 4-6:3 sets × 8 repetitions.

All training sessions were supervised by the experienced kinesiologist.

2.3 | Assessment of morphological and architectural characteristics

Height, body mass, body fat percentage, and muscle mass percentage were measured using stadiometer and multi-frequency bio-impedance scale (Tanita MC-980MA, Tanita,).

Resona 7 diagnostic ultrasound (Mindray, Mindray Medical International Limited) and middle-sized linear probe (Model L11-3U, Mindray) were used to record an extended field-of-view image of the BFlh on the dominant (ie, kicking)

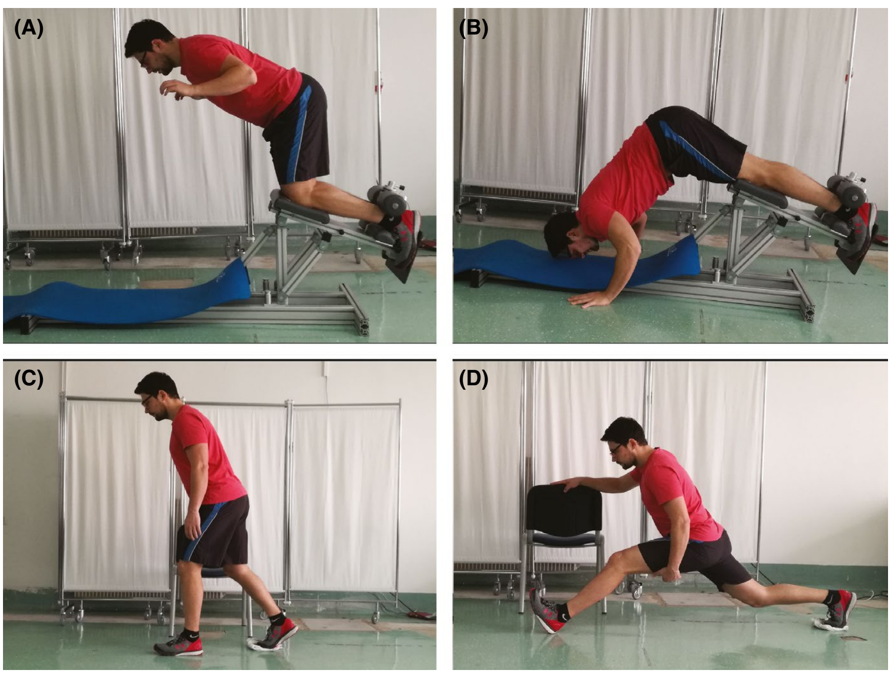

FIGURE 1 The modified Nordic hamstring exercise (starting position A, final position B) and the glider (starting position C, final position D)

leg. Extended field-of-view was used instead of a single image extrapolation method, as seen and recommended in previous studies.[17,18] Two separate images of the BFlh were recorded in a relaxed position, with participants lying prone on a physio bed with knee and hip joint angles at 0°, ie, full extension). BFlh muscle-tendon complex was marked on the skin with the help of palpation and isometric contractions. The distance between the BFlh origin and insertion was measured to later determine the middle point at which the muscle architecture data were acquired. The ultrasound scan was then taken by continuously and steadily moving the probe along the marked line in a 3-5 s time window, starting at the insertion of BFlh. The ultrasound probe was changed throughout the experiment so that it remained perpendicular to the skin and directed according to the fascicle orientation of the BFlh.[17] During ultrasound image acquisition, a consistent minimal pressure was applied on the skin. Water-soluble, hypoallergenic ultrasound gel (AquaUltra Basic, Ultragel) was used to improve acoustic contact between the probe and skin. Of the two recorded images, the one with better visible muscle fibers and aponeuroses was selected and processed in a publicly available digitizing software program ImageJ (National Institutes of Health, Bethesda) by setting the appropriate scale and using the "straight/segmented line tool" or "angle tool." The measurement place—region of interest—was determined using a measuring scale on an ultrasound image at the middle of the BFlh muscle-tendon complex based on the previously measured distance between BFlh origin and insertion (50% of the distance). The following data were acquired at the region of interest from the selected images (Figure 2): muscle thickness (the shortest distance from the superficial to the mid-muscle aponeurosis), pennation angle (angle between the muscle fascicle and the mid-muscle aponeurosis), and muscle fascicle length (from the mid-muscle aponeurosis origin to the superficial aponeurosis insertion). Three muscle fascicles were measured on each image in the range of 3 cm at the middle of the BFlh; the average of the three measurements was used for statistical analysis.[17] All images were processed by the experienced radiologist, who was blinded to the participants' group.

2.4 | Assessment of functional characteristics

Following the assessment of morphological and architectural characteristics, participants warmed up with light aerobic activity (5 min of alternating stepping on a 25 cm high box), and dynamic stretching and strengthening bodyweight exercises with the emphasis on trunk and lower limb muscles (5 min). After the warm-up, the first test was always the measurement of the hamstrings' activation level followed by other tests of functional characteristics (described below) in a randomized order. The rest between consecutive repetitions and between tests lasted for 30 s and 5-8 min, respectively, to minimize fatigue. For all the tasks tested, the subject first performed familiarization trials (~50%, ~75%, and ~90% of the maximal effort) followed by the true testing trials.

2.4.1 | Isokinetic dynamometry

Isokinetic dynamometer (Humac Norm, Computer Sports Medicine Inc) was used to assess isokinetic concentric and eccentric knee flexor strength on the dominant leg. Measurements were taken in a seated position with the 90° hip flexion. Thigh of the working leg, hip, and trunk were stabilized with fixation straps. The dynamometer settings were individually adjusted to align the axis of rotation with the lateral femoral condyle of the knee. The resistance pad was placed and secured proximal to the medial malleolus. Before measurements, gravity correction factor was determined using the standard routine of the device by measuring the torque exerted on the resistance pad with the knee in extension and the leg in a relaxed state and was applied within the acquisition software. Range of motion was set to 90° from 95° to 5° (0° representing full knee extension). Participants performed three familiarization trials (five repetitions per trial, gradually increasing the effort) prior to the main testing sets: two trials of five concentric and eccentric repetitions at the angular speed of 60 and 180°/s in a randomized order, respectively. The rest between the testing trials was set to three

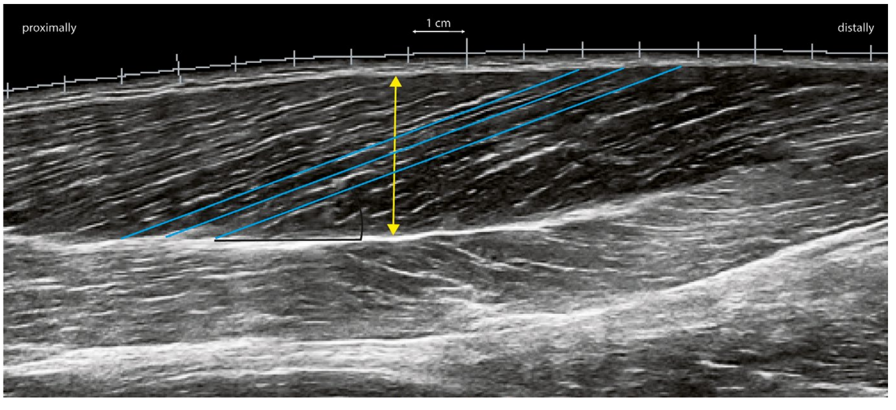

FIGURE 2 Example of extended field-of-view ultrasound image of long head biceps femoris. Measured parameters: muscle thickness (yellow arrow), fascicle length (blue solid lines), and pennation angle (black curved line)

minutes. To avoid the effects of acceleration and deceleration of the lever arm on torque output, only peak torque data from a timeframe with constant velocity movement were used in data analysis. Peak eccentric and concentric knee flexor torques and knee angles at which the peak torques were recorded from each repetition were averaged and used for the analysis. All isokinetic measurements were performed by the same experienced researcher.

2.4.2 | Knee flexion isometric peak torque and level of activation

A knee dynamometer (S2P Ltd., Science to practice) was used to assess knee flexion isometric peak torque and knee flexors activation level on the dominant leg.[19] Subjects were in a seated position with 60° knee flexion (0° representing full knee extension) and 90° hip flexion. Knee axis was aligned with the axis of the dynamometer's leaver arm. The shank support was positioned superior to the lateral malleolus. The hips were stabilized with a fixation strap over the pelvis. Subjects performed three 3-s knee flexion maximal voluntary isometric contractions separated by 60-s rest intervals. Custom built software (ARS dynamometry, S2P Ltd.) was used for the signal processing and quantification. Highest average on 1-s time interval for each repetition was calculated and taken as a peak torque. For analysis, maximum of three repetitions peak torques were used.

For assessing the activation level, double twitch interpolated method was used with a direct muscle stimulation, applied to the hamstrings with self-adhesive surface electrodes (Axelgaard manufacturing Co., Ltd.). Four electrodes (two beneath the gluteal fold and two superior to the popliteal fossa) were placed on the skin. High-voltage electrical stimulator (model ETA 400, EMF-Furlan & Co Ltd.) was used for stimulation with square-wave, biphasic doublets at 100 Hz (10-ms interstimulus interval) with the maximal voltage of 400 V. Prior to testing, brief electrical pulses of submaximal intensity were delivered to familiarize the participants to the electrical pulses. The intensity of stimulation used during testing was determined at rest by gradually increasing the current in 10 mA, until the stimulation-induced torque no longer increased. The stimulation intensity at maximum twitch torque was further increased by 30% to secure the supramaximal stimulation level.[20]

Two separated trains of electrical pulses were then imposed: first during the maximal contraction (when torque reached a visible plateau) and second approx. 3-s after the end of contraction when subject relaxed. Highest average on 1-s time interval peak torque of maximal contraction prior to stimulation (a), stimulation-induced peak torque immediately after stimulation (b), and peak torque of the resting potentiated twitch were recorded (c). Percentage of the voluntary activation was then calculated using the following equation: $(1 - (b - a)/c) \times 100$ for each repetition, and the average of the three repetitions was used in analysis.

2.4.3 | Nordic hamstring exercise peak torque

Contact forces were measured during the NHE at a sampling rate of 500 Hz at the ankle support using a built-in dynamometer (OptoForce 3D) on the NHE device and custom written analysis software (LabVIEW, National Instruments). Participants were instructed to (a) maintain neutral hip position; (b) descend steadily as long as they can in a controlled manner in 3-5 seconds; and (c) position the hands along the body, with an approximately 130° elbow flexion. All the repetitions were supervised by the kinesiologist; in case of incorrect execution, the repetition was repeated. The knee torque was calculated using peak forces and lower leg effective lengths (measured from the lateral malleoli to the lateral condyle of tibia) and was normalized to participants' bodyweight. Peak torques of three repetitions were recorded; the highest value was used for data analysis. Since the NHE test is bilateral, we have reported results as a sum of normalized peak torque of the dominant and non-dominant leg.

2.4.4 | Countermovement jump

Limited evidence exists regarding the effects of eccentric hamstrings training on explosive movement performance.[14] We, therefore, included measurement of lower-body power using a countermovement jump test. Three countermovement jumps were performed on a piezo-electric force plate (Kistler, model 9260AA6), separated by 60-s-long rest intervals. The participants started in an upright stance position (feet shoulder width apart) with hands on hips. From this position, they rapidly accelerated downward by flexing in the knees and hips, followed by immediate extension in the knees, hips, and ankles to jump as high as possible. Hands were positioned on hips throughout the entire jump. Commercially available software (ARS dynamometry, S2P Ltd.) was used to acquire the signals at 1000 Hz and filter them with a low-pass Butterworth filter (20 Hz cutoff frequency, 2nd order). Countermovement jump height and average power were calculated as follows:

$$H = \frac{\left[\frac{\int_{\mathrm{Start}}^{\mathrm{Take\ Off}} [F(t) - \mathrm{BW}(t)]dt}{\mathrm{BM}}\right]^2}{2 \times g}, \tag{1}$$

$$P_{\mathrm{avg}} = \mathrm{avg}\left(\left[\int_{\mathrm{Start}}^{\mathrm{Take\ Off}} \left[\frac{F(t)}{\mathrm{BM}} - g\right] dt\right] \times F(t)\right). \tag{2}$$

where H—jump height, P_{avg}—average power, $F(t)$—vertical force, BW(t)—body weight, BM—body mass, g—gravitational constant, Start [s]—the start of the jump action, and Take Off [s]—the start of the flight phase. Results from the best repetition (based on jump height) were further analysed.

For all measurements of functional capabilities, loud verbal encouragement was provided to help facilitate participants' maximal efforts.

2.5 | Statistical analysis

The data were statistically processed in the SPSS 25 computer program (IBM). Descriptive statistics were calculated and reported as mean ± SD in addition to the 95% confidence intervals. Shapiro-Wilk test was used for testing of normality. Inter-session reliability of all dependent variables was assessed on participants in the control group. Coefficient of variation (CV) was calculated as the quotient between the typical error of measurement and average of both sessions, expressed in %. Intra-class correlation coefficient was calculated using a 2-way random model with absolute agreement ($ICC_{2,k}$). Differences among corresponding variables were assessed using a repeated measures analysis of variance, testing for interaction between time (pre- vs post-intervention) and group (control vs intervention). Where interaction effect was statistically significant, one-tailed (due to the expected direction of parameter changes) t test with Bonferroni's correction was used to test the pre-post difference in each group. Effect sizes were calculated for the pairwise comparisons using the Cohen's d method and interpreted trivial (≤0.20), small (0.20-0.59), moderate (0.60-1.19), large (1.20-1.99), or very large (≥2.00).[21] The level of statistical significance was set at $P < .05$.

3 | RESULTS

3.1 | Reliability of dependent variables

Inter-session reliability was calculated based on the pre-intervention (session 1) and post-intervention (session 2) measurements of the control group (16 participants). Main results of inter-session reliability analyses of all dependent variables are presented in Table 2. Overall, selected architectural and functional hamstring characteristics had high reliability—no systematic bias, within-individual variation (CV) below 10%, and test-retest reliability ($ICC_{2,k}$) above 0.80. The exceptions were concentric and eccentric angles of peak torque, and the concentric isokinetic hamstring peak torque at 60 and 180°/s that displayed systematic bias (only for the concentric isokinetic hamstring peak torque at 60 and 180°/s), relatively high within-individual variability (CV = ~15%-40%), and low to moderate test-retest reliability ($ICC_{2,k}$ = 0.12-0.70). Moderate test-retest reliability ($ICC_{2,k}$ = 0.67), but without systematic bias and acceptable within-individual variation (CV = 10%), was also observed for voluntary activation level.

3.2 | Compliance

Participation in the training program was registered each session; median number of performed sessions was 11 (eight subjects had 100%, six subjects missed one session, two subjects missed two sessions, two subjects missed three sessions out of 12).

3.3 | Architectural characteristics

Table 3 shows descriptive statistics of the architectural characteristics of BFlh. Individual data of fascicle length and pennation angle are shown in the supplementary file. A significant interaction (time × group) effect was observed for: pennation angle ($F = 11.902$, $P = .001$) and fascicle length ($F = 9.881$, $P = .004$), but not for muscle thickness ($F = 2.249$, $P = .144$). Post-hoc testing revealed significant increase in fascicle length (+6.9%; $P < .01$; $d = 1.12$) and a significant decrease in pennation angle (−12.9%; $P < .01$; $d = 1.31$) of BFlh in the intervention group, while no significant changes were observed in the control group (P = .40-.42; d = 0.05-0.06).

3.4 | Strength, power, and voluntary activation level

Table 4 shows descriptive statistics for knee flexion concentric and eccentric isokinetic torque measurements at 60 and 180°/s. A significant interaction (time × group) effect was observed for concentric and eccentric peak torque at 60°/s ($F = 4.994$, $P = .033$; $F = 7.481$, $P = .010$) and also for concentric and eccentric peak torque at 180°/s, ($F = 9.193$, $P = .005$; $F = 4.251$, $P = .048$). Peak torque angles were not significantly affected by the intervention (mean change: 4.1-8.0°; P = .09-.10, d = 0.33-0.35). Post-hoc testing revealed significant increase in concentric and eccentric peak torque at 60°/s (+15.3% and +14.6%, $P < .03$, d = 0.55-0.62) and in concentric peak torque at 180°/s (+19.7%, $P < .01$, $d = 0.99$) in the intervention group. Changes in the eccentric peak torque at 180°/s in the intervention group were present, but were not statistically significantly (+10.1%, $P = .052$, $d = 0.42$). No significant changes in knee flexion isokinetic performance in the control group were observed (P = .11-.47, d = 0.04-0.32), except a decrease in the eccentric peak torque at 60°/s ($P = .03$, $d = 0.54$).

TABLE 2 Reliability of architectural and functional characteristics of hamstrings

Task	Session 1 mean (SD)	Session 2 mean (SD)	CV	$ICC_{2,k}$	Bias *F*	*P*
CMJ height (m)	0.3 (0.06)	0.29 (0.08)	6.36	0.89	0.26	.62
CMJ average power (W/kg)	24.89 (5.09)	24.68 (5.24)	4.43	0.91	0.08	.79
Torque 60°/s CON (Nm/kg)	1.18 (0.33)	1.36 (0.29)	8.70	0.82	14.09	.00
Angle 60°/s CON (Nm/kg)	24.88 (8.88)	23.23 (6.38)	25.41	0.12	0.4	.57
Torque 60°/s ECC (Nm/kg)	1.88 (0.33)	1.79 (0.38)	15.24	0.66	1.11	.31
Angle 60°/s ECC (Nm/kg)	19.32 (11.85)	16.95 (8.52)	40.75	0.34	0.37	.55
Torque 180°/s CON (Nm/kg)	0.76 (0.32)	1.02 (0.23)	15.47	0.61	16.74	.00
Angle 180°/s CON (Nm/kg)	27.8 (3.25)	28.01 (1.72)	9.31	0.54	0.04	.84
Torque 180°/s ECC (Nm/kg)	1.77 (0.38)	1.78 (0.34)	5.16	0.85	0.02	.89
Angle 180°/s ECC (Nm/kg)	22.64 (6.64)	20.72 (4.98)	16.14	0.71	1.96	.18
NHE PT (Nm/kg)	2.99 (0.60)	2.89 (0.80)	9.56	0.80	0.40	.54
ISO knee flexion PT (Nm/kg)	1.52 (0.34)	1.48 (0.4)	5.18	0.90	0.37	.56
Activation level (%)	94.59 (5.76)	89.96 (9.37)	10.17	0.67	2.61	.13
Pennation angle (º)	11.76 (2.35)	11.85 (2.34)	4.38	0.91	0.06	.80
Fascicle length (cm)	7.98 (1.11)	7.94 (1.1)	2.67	0.92	0.04	.84
Muscle thickness (cm)	1.94 (0.34)	1.97 (0.37)	2.68	0.94	0.57	.46

Abbreviations: CMJ, countermovement jump; CON, concentric; CV, coefficient of variation (%); ECC, eccentric; *F*, *F* ratio in analysis of variance; ICC, intra-class correlation coefficient; *P*, level of statistical significance.

TABLE 3 Architectural characteristics of biceps femoris long head

	Control group				Intervention group			
	PRE	95% CI	POST	95% CI	PRE	95% CI	POST	95% CI
Pennation angle (º)	11.76 ± 2.35	10.51-13.02	11.85 ± 2.34	10.6-13.1	13.91 ± 2.95	12.21-15.2	12.32 ± 2.39**	10.95-13.42
Fascicle length (cm)	7.98 ± 1.11	7.38-8.57	7.94 ± 1.10	7.36-8.53	7.74 ± 0.82	7.27-8.00	8.32 ± 0.85**	7.84-8.73
Muscle thickness (cm)	1.94 ± 0.34	1.75-2.12	1.97 ± 0.37	1.77-2.16	1.97 ± 0.34	1.78-2.13	2.09 ± 0.31	1.91-2.22

Abbreviations: CI, confidence interval; POST, post-intervention; PRE, pre-intervention; SIG, significant time (pre vs post) × group (control vs intervention) interaction.

**$P < .01$.

Table 5 shows descriptive statistics for the rest of the measured functional parameters. Individual data of NHE peak torque are shown in the supplementary file. A significant interaction (time × group) effect was observed for NHE peak torque ($F = 14.873$, $P = .001$), isometric knee flexion peak torque ($F = 5.450$, $P = .026$), and hamstring voluntary activation level ($F = 18.294$, $P = .000$), but not for countermovement jump height or power ($F = 0.060$, $P = .809$; $F = 0.015$,

TABLE 4 Peak torques and knee flexion angles on isokinetic dynamometer

	Control group				Intervention group			
	PRE	95% CI	POST	95% CI	PRE	95% CI	POST	95% CI
Torque, 60°/s CON (Nm/kg)	1.81 ± 0.07	1.24-1.53	1.82 ± 0.07	1.24-1.55	1.33 ± 0.42	1.11-1.54	1.57 ± 0.36*	1.38-1.75
Angle, 60°/s CON (°)	24.88 ± 8.88	20.14-29.61	23.23 ± 6.38	19.82-26.63	23.37 ± 12.72	16.83-29.91	19.31 ± 6.44	16.00-22.62
Torque, 60°/s ECC (Nm/kg)	2.50 ± 0.08	1.78-2.13	2.50 ± 0.09	1.67-2.05	1.79 ± 0.55	1.5-2.07	2.09 ± 0.52*	1.83-2.36
Angle, 60°/s ECC (°)	19.32 ± 11.85	13-25.63	16.95 ± 8.52	12.41-21.49	21.10 ± 18.84	11.41-30.79	13.13 ± 8.62	8.70-17.57
Torque, 180°/s CON (Nm/kg)	1.05 ± 0.24	0.92-1.18	1.04 ± 0.23	0.92-1.16	0.93 ± 0.33	0.77-1.1	1.16 ± 0.27**	1.02-1.30
Angle, 180°/s CON (°)	27.80 ± 3.25	26.07-29.53	28.01 ± 1.72	27.09-28.92	28.99 ± 6.26	25.77-32.2	28.11 ± 4.31	25.89-30.32
Torque, 180°/s ECC (Nm/kg)	1.86 ± 0.34	1.68-2.04*	1.79 ± 0.34	1.61-1.97	1.70 ± 0.51	1.44-1.97	1.9 ± 0.41*	1.68-2.11
Angle, 180°/s ECC (°)	22.64 ± 6.64	19.1-26.17	20.72 ± 4.98	18.07-23.38	26.35 ± 15.11	18.58-34.12	25.61 ± 13.51	18.66-32.56

Abbreviations: CON, concentric phase; ECC, eccentric phase; POST, post-intervention; PRE, pre-intervention; SIG, significant time (pre vs post) × group (control vs intervention) interaction.

*$P < .05$.

**$P < .01$.

P = .903). Post-hoc testing revealed significant increase in NHE peak torque (+24.8%, $P < .01$; $d = 1.19$), isometric knee flexion peak torque (+14.0%, $P < .01$; $d = 0.73$), and hamstring voluntary activation level (+9.8%, $P < .01$; $d = 1.29$) in the intervention group. No significant changes in the corresponding variables were observed in the control group (P = .06-.43; d = 0.04-0.40).

4 | DISCUSSION

The aim of this study was to investigate the effects of the 6-week progressive eccentric hamstring training in a lengthened position on architectural and functional characteristics of hamstring muscles. Our results revealed the significant time × group interaction effect for most architectural characteristics (BFlh fascicle length and pennation angle) and functional capabilities of the hamstrings (isokinetic and isometric peak torque, NHE peak torque, and hamstring voluntary activation level).

4.1 | Architectural characteristics

As hypothesized, eccentric hamstring training in a lengthened position significantly increased BFlh fascicle length. Since shorter fascicle length of BFlh muscle has been recognized as a risk factor for HSIs,[5] the observed architectural changes in BFlh following long-muscle eccentric training could be regarded as favorable in terms of prevention and rehabilitation of HSIs. To our best knowledge, only Guex et al[11] have investigated hamstring architectural adaptations following long-muscle length eccentric training and reported significantly greater increase in BFlh fascicle length in long- vs short-muscle length training group (d = 0.89 vs 0.57). The magnitude of increase in BFlh fascicle length, observed in the current study (d = 1.12), is higher than the one observed in Guex et al study,[11] and in seven[22-29] (d = 0.09-0.72) out of thirteen previous eccentric training studies performed at short-muscle length. Notably, those previous studies[15,22-33] had very large variability in training effects on BFlh fascicle length (d = 0.08-3.46). Given that recent studies reported similar BFlh architectural adaptations following (a) low- vs high-volume eccentric training,[15,23] and (b) short-duration (4 weeks)[27] vs long-duration (10 weeks)[30] eccentric training, the overall training volume is unlikely to be responsible for the very large inter-study variability in training effects on BFlh fascicle length. Other relevant factors could be the training status of participants and methodology of recording and analyzing ultrasound images (extended field-of-view vs single image extrapolation method). Indeed, training studies[23,25,28] that have included highly trained athletes, or have used extended field-of-view method for measuring BFlh architecture,

TABLE 5 Nordic hamstring exercise peak torque, countermovement jump, isometric knee flexion torque, and hamstring voluntary activation level

	Control group				Intervention group			
	PRE	95% CI	POST	95% CI	PRE	95% CI	POST	95% CI
NHE PT (Nm/kg)	2.99 ± 0.60	2.66-3.32	2.89 ± 0.80	2.45-3.34	2.29 ± 0.76	1.90-2.68	3.04 ± 0.55**	2.76-3.33
CMJ height (m)	0.31 ± 0.07	0.27-0.35	0.31 ± 0.07	0.27-0.35	0.32 ± 0.09	0.28-0.37	0.32 ± 0.09	0.28-0.37
CMJ average power (W/kg)	25.40 ± 5.39	22.41-28.38	25.71 ± 5.08	22.9-28.52	25.37 ± 4.87	22.95-27.79	25.35 ± 4.91	22.9-27.79
ISO knee flexion PT (Nm/kg)	1.51 ± 0.34	1.33-1.70	1.48 ± 0.40	1.27-1.69	1.32 ± 0.47	1.07-1.57	1.54 ± 0.48*	1.3-1.8
Activation level (%)	94.6 ± 5.8	91.5-97.7	90.0 ± 9.4	85.0-95.0	85.3 ± 7.6	81.5-89.5	94.5 ± 4.1**	92.2-96.3

Abbreviations: CMJ, countermovement jump; ISO, isometric; NHE, Nordic hamstring exercise; POST, post-intervention; PRE, pre-intervention; PT, peak torque; SIG, significant time (pre vs post) × group (control vs intervention) interaction.

*$P < .05$.

**$P < .01$.

reported generally small increases in BFlh fascicle length ($d = 0.35$-0.58). Recently, Pimenta et al[17] have reported significant differences in BFlh fascicle length measured using single image extrapolation method vs extended field-of-view method and concluded that these differences are large enough to affect muscle function and injury risk assessment. More recently, Franchi and co-workers[18] have shown that extrapolation methods used for estimating BFlh fascicle length from single ultrasound images with a 5-cm field of view overestimates its length when compared with extended field-of-view scans. The authors recommended that extended field-of-view method should be implemented to accurately determine intervention-related changes in BFlh fascicle length. Future intervention studies should, therefore, employ extended field-of-view method for measuring architectural characteristics of hamstring muscles.

In the present study, we have also observed the small increase in muscle thickness and the large decrease in pennation angle of BFlh. Regarding BFlh muscle thickness, our findings are in line with some,[15,25,27,32,33] but not all previous research.[22,28-31] Exercise choice could be one factor responsible for the observed discrepancy in results. Indeed, Hegyi et al[34] have recently demonstrated that the semitendinosus-to-BFlh activity ratio is higher during modified NHE (ie, hip flexed at 90°) compared with the standard NHE. It should be also noted that BFlh muscle activity during standard NHE (99.7% MVC)[7] is higher than during the modified NHE (80% MVC)[5] and the glider (50%-60% MVC).[12] Although we have added additional loads to both exercises during the intervention, it is possible that lower activity of BFlh in these exercises could have contributed to a smaller increase in BFlh muscle thickness. Another factor that could affect hypertrophic response of BFlh to eccentric training is intervention duration. The fact that studies that have reported significant and practically relevant increase in BFlh muscle thickness lasted 8-12 weeks[22,24,28-30] supports this view.

Regarding the pennation angle of BFlh, Guex et al[11] have reported only a small decrease after 3-week eccentric hamstrings training at long-muscle length. Moderate to large decreases in pennation angle of BFlh following eccentric training at short-muscle length were observed by several other research groups.[22,27,31,33] In contrast, Lowell et al[24] have reported either no change or a small increase in pennation angle of BFlh following NHE training performed before vs after soccer practice. However, the authors reported rather low compliance (41%) with the training intervention in both groups. Recent resistance training literature review[35] indicates that the concentric training results in an increase in pennation angle with muscle hypertrophy, while variable effects (ie, an increase, no change, or a decrease) in pennation angle of trained muscles were seen following eccentric training. While an increase in pennation angle is considered as a space-saving strategy for packing muscle fibers with increased diameters into a limited area of aponeurosis,[35] the functional relevance of a decrease in pennation angle of BFlh following eccentric training is currently unclear and requires further research.

Taken together, present results indicate that eccentric hamstring strengthening program at long-muscle length increases BFlh fascicle length and decreases its pennation angle, and the magnitude of these effects is comparable to, or even larger than, those observed with eccentric hamstring training at short-muscle length. However, caution is needed when comparing present results with previous research as vast majority of previous studies estimated BFlh fascicle length from single ultrasound image, a method which significantly overestimates its length when compared with extended field-of-view method used in the current study.[18]

4.2 | Strength, power, and voluntary activation level

Numerous previous studies have evaluated the effects of eccentric hamstring strengthening at short-muscle length on hamstrings muscle performance and reported significant increases in eccentric[15,22,24,27,30,31,33,36,37] and concentric hamstring strength.[14,28,32] In line with previous research, we have also observed significant increases in eccentric, isometric, and concentric hamstring strength following eccentric hamstring training at long-muscle length. Our results also compare well with the results of only published study[11] that has compared the effects of 3-week isokinetic eccentric hamstring training at short vs long-muscle length. However, those authors failed to observe changes in concentric hamstrings strength, possibly due to relatively short duration of the intervention or somewhat higher within-individual variation of concentric isokinetic hamstring peak torques at 60 and 180°/s (see Table 2).

In the present study, we have measured the eccentric hamstring strength with both isokinetic dynamometry and NHE testing device. In line with the principle of training specificity, the observed gains in eccentric hamstrings strength in the current study were larger in the test that was similar to the exercise(s) used, that is, in the NHE test (d = 1.2) vs the isokinetic eccentric test (d = 0.42-0.55). Recent evidence strongly suggests that the two strength tests measure different functional characteristics of hamstring muscles.[38] Since eccentric hamstring strength measured with NHE testing device,[5] but not with isokinetic device,[39] is a significant risk factor for HSI, it is important to note that the observed increase in eccentric strength measured in the NHE test is larger than,[27,33] or comparable to,[15,31] the vast majority of eccentric training studies performed at short-muscle length. Only Bourne et al[30] reported larger gains in eccentric strength in the NHE test following NHE training (d = 2.36). However, their training intervention lasted 4 weeks longer than the one in the current study (ie, 10 vs 6 weeks). These results generally support the notion that hamstring training focused on reducing the risk of HSI occurrence and performance enhancement should also include exercise(s) at long-muscle length. However, we must acknowledge that the applied intervention had no effect on lower-body power in vertical jumping. Although hamstring muscles might have a more significant role in performance of other rapid movements like sprints, we expected that eccentric hamstring strengthening would also improve performance in vertical jump. Contrary to our findings, Clark et al[14] have reported a 6.6% increase in vertical jump height following only eight NHE training sessions. The fact that their subjects had no previous strength training experience and that the authors used different vertical jump test and measuring methodology (countermovement jump vs countermovement jump with arm swing; force plate vs Vertec device) could be responsible for this discrepancy in result. Future studies are needed to evaluate the effects of eccentric hamstring strengthening at long-muscle length on rapid movement performance, particularly sprinting as it represents a major HSI mechanism.

The novel finding of the current study is large training-induced increase (+10%; d = 1.29) in voluntary activation level of hamstring muscles, which suggests that the abovementioned gains in isometric, concentric, and eccentric hamstrings strength are, at least in part, the result of increased neural drive to agonist muscles. Most previous studies focused only on architectural/morphological adaptations to eccentric hamstring training.[15,22,23,25-33] Significant increases in EMG activity of hamstrings have been previously reported.[24,37] These results, together with our findings strongly suggest that changes in eccentric hamstring strength are attained via increased agonist voluntary activation.

One potentially relevant functional characteristics of hamstring muscles in reducing the risk of HSI occurrence is the angle of peak torque. Specifically, it has been suggested that eccentric training may reduce HSI rates as the muscles are trained to shift the peak of the torque-angle curve in the direction of longer muscle lengths.[13] Previous studies that have used eccentric training at short-muscle length (mainly NHE) have reported either no change,[37] or a significant shift in angle of hamstring peak torque toward longer muscle lengths that ranged between 4.0 and 9.1°.[13,14] Our results do not show a significant change, in contrast to Guex et al[11] who have reported much larger (17.3°) shifts in angle of hamstrings peak torque toward longer muscle length after only 3 weeks of isokinetic eccentric hamstring strengthening at long-muscle lengths. This rather large discrepancy in results could be explained with very low retest reliability and high variability of this parameter (see Table 2), thereby questioning its sensitivity to detect real changes in torque development throughout the range of motion.[24]

Present results related to functional characteristics of hamstrings could have significant practical implications. Namely, it has been shown that low NHE strength represents a significant risk factor for HSIs.[5] Furthermore, Buchmann et al[40] have recently reported that moderate to severe HSI is associated with long-term deficits in voluntary activation during maximal eccentric contraction. From that perspective, the observed training-induced increase in NHE strength and voluntary activation level of hamstring muscles suggest that the applied eccentric hamstring training at long-muscle length could be an effective strategy for reducing the risk of HSIs occurrence as well as for rehabilitation of HSIs; however, future prospective studies are needed to verify this conjecture.

Some limitations of the present study should be acknowledged. First, we failed to measure training-induced changes in architecture of all hamstring muscles but focused only on most often injured one, that is, BFlh. Additionally, the results of our analysis on only the middle part of the BFlh may not reflect changes in architectural properties on the distal or proximal part of the muscle, since architectural changes may be region-specific. This limits us in our conclusions regarding architectural adaptations to long-length eccentric training that may underpin the observed strength gains in hamstring muscles. Second, we did not evaluate the effects of the applied eccentric hamstring strengthening on sprint performance and its mechanical underpinnings, which would increase the ecological validity and practical implications of the current study. Third, despite our recreationally active participants displaying similar NHE eccentric strength as Australian football players,[5] it remains to be seen if our results are applicable to athletic population competing in high-speed running sports.

5 | CONCLUSION

In conclusion, the present study demonstrated that the progressive 6-week eccentric hamstring training protocol at long-muscle length induces significant positive architectural and neuromuscular adaptations in the hamstring muscles that are comparable to, or even higher than, the one observed with eccentric hamstring training at short-muscle length. Nonetheless, future randomized controlled studies are needed to compare the effectiveness of eccentric training at short and long-muscle length, as well as their combinations, on HSI risk factors and injury mechanisms (ie, sprint mechanics and performance).

6 | PERSPECTIVE

This study is the first to demonstrate significant and favorable changes in hamstring architectural and functional characteristics following simple, feasible, and widely accessible eccentric exercise training at long-muscle length. Our results suggest that improved hamstrings performance following eccentric training at long-muscle length is the result of both architectural and neural adaptations. Assuming fascicle length, NHE strength and hamstring voluntary activation as factors relevant for reducing the risk of HSIs occurrence and rehabilitation of HSIs, the observed training-induced increase in (a) BFlh fascicle length, (b) eccentric and NHE strength, and (c) hamstring voluntary activation level suggest that the applied eccentric training at long-muscle length could be of practical value in sports and rehabilitation settings.

ACKNOWLEDGMENTS

The study was supported by the Slovenian Research Agency through the program "Kinesiology of monostructural, polystructural and conventional sports" [P5-0147 (B)] and the project TELASI-PREVENT [L5-1845] (Body asymmetries as a risk factor in musculoskeletal injury development: studying aetiological mechanisms and designing corrective interventions for primary and tertiary preventive care).

CONFLICT OF INTEREST

Authors declare that they have no conflict of interest.

ORCID

Jan Marušič https://orcid.org/0000-0001-9547-3748
Goran Marković https://orcid.org/0000-0002-9009-6493
Nejc Šarabon https://orcid.org/0000-0003-0747-3735

REFERENCES

1. Erickson LN, Sherry MA. Rehabilitation and return to sport after hamstring strain injury. *J Sport Health Sci*. 2017;6(3):262-270.
2. Maniar N, Schache A, Heiderscheit B, Opar D.Hamstrings biomechanics related to running. In: Thorborg K, Opar D, Shield A, eds. *Prevention and Rehabilitation of Hamstring Injuries*. Cham, Switzerland: Springer AG; 2020: 65–82.
3. Lieber RL, Fridén J. Muscle damage is not a function of muscle force but active muscle strain. *J Appl Physiol (1985)*. 1993;74(2):520-526.
4. Mair SD, Seaber AV, Glisson RR, Garrett WE Jr. The role of fatigue in susceptibility to acute muscle strain injury. *Am J Sports Med*. 1996;24(2):137-143.
5. 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(21):1362-1370.
6. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. *Br J Sports Med*. 2016;50(24):1524-1535.
7. Šarabon N, Marušič J, Marković G, Kozinc Ž. Kinematic and electromyographic analysis of variations in Nordic hamstring exercise. *PLoS ONE*. 2019;14(10):1-16.
8. Oakley AJ, Jennings J, Bishop CJ. Holistic hamstring health: not just the Nordic hamstring exercise. *Br J Sports Med*. 2018;52(13):816-817.

9. Askling CM, Tengvar M, Thorstensson A. Acute hamstring injuries in Swedish elite sprinters and jumpers: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. *Br J Sports Med*. 2013;47:953-959.
10. Tyler TF, Schmitt BM, Nicholas SJ, McHugh MP. Rehabilitation after hamstring-strain injury emphasizing eccentric strengthening at long muscle lengths: results of long-term follow-up. *J Sport Rehabil*. 2017;26(2):131-140.
11. Guex K, Degache F, Morisod C, Sailly M, Millet GP. Hamstring architectural and functional adaptations following long vs. short muscle length eccentric training. *Front Physiol*. 2016;7:1–9.
12. Severini G, Holland D, Drumgoole A, Delahunt E, Ditroilo M. Kinematic and electromyographic analysis of the Askling L-Protocol for hamstring training. *Scand J Med Sci Sport*. 2018;28(12):2536-2546.
13. Brughelli M, Mendiguchia J, Nosaka K, Idoate F, Arcos AL, Cronin J. Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Phys Ther Sport*. 2010;11(2):50-55.
14. Clark R, Bryant A, Culgan JP, Hartley B. The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. *Phys Ther Sport*. 2005;6(2):67-73.
15. Presland JD, Timmins RG, Bourne MN, Williams MD, Opar DA. The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. *Scand J Med Sci Sport*. 2018;28(7):1775-1783.
16. Cuthbert M, Ripley N, McMahon JJ, Evans M, Haff GG, Comfort P. The effect of nordic hamstring exercise intervention volume on eccentric strength and muscle architecture adaptations: a systematic review and meta-analyses. *Sports Med*. 2020;50(1):83-99.
17. Pimenta R, Blazevich AJ, Freitas SR. Biceps femoris long-head architecture assessed using different sonographic techniques. *Med Sci Sports Exerc*. 2018;50(12):2584-2594.
18. Franchi MV, Fitze DP, Raiteri BJ, Hahn D, Spörri J. Ultrasound-derived biceps femoris long-head fascicle length: extrapolation pitfalls. *Med Sci Sport Exerc*. 2020;52(1):233-243.
19. Sarabon N, Rosker J, Fruhmann H, Burggraf S, Loefler S, Kern H. Reliability of maximal voluntary contraction related parameters measured by a novel portable isometric knee dynamometer. *Phys Medizin Rehabil Kurortmedizin*. 2013;23(1):22-27.
20. Marshall PWM, Lovell R, Jeppesen GK, Andersen K, Siegler JC. Hamstring muscle fatigue and central motor output during a simulated soccer match. *PLoS ONE*. 2014;9(7):e102753.
21. Hopkins WG. Linear models and effect magnitudes for research. Clinical and practical applications. *Sportscience*. 2010;14:49-58.
22. 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(1):88-94.
23. Lacome M, Avrillon S, Cholley Y, Simpson BM, Guilhem G, Buchheit M. Hamstring eccentric strengthening program: does training volume matter? *Int J Sports Physiol Perform*. 2020;15(1):81-90.
24. Lovell R, Knox M, Weston M, Siegler JC, Brennan S, Marshall PWM. Hamstring injury prevention in soccer: before or after training? *Scand J Med Sci Sport*. 2018;28(2):658-666.
25. Mendiguchia J, Conceição F, Edouard P, et al. Sprint versus isolated eccentric training: Comparative effects on hamstring architecture and performance in soccer players. *PLoS ONE*. 2020;15(2):e0228283.
26. Potier TG, Alexander CM, Seynnes OR. Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. *Eur J Appl Physiol*. 2009;105(6):939-944.
27. Ribeiro-Alvares JB, Marques VB, Vaz MA, Baroni BM. Four weeks of nordic hamstring exercise reduce muscle injury risk factors in young adults. *J Strength Cond Res*. 2018;32(5):1254-1262.
28. Severo-Silveira L, Dornelles MP, Lima-e-Silva FX, et al. Progressive workload periodization maximizes effects of nordic hamstring exercise on muscle injury risk factors. *J Strength Cond Res*. 2018;1.
29. Seymore KD, Domire ZJ, DeVita P, Rider PM, Kulas AS. The effect of Nordic hamstring strength training on muscle architecture, stiffness, and strength. *Eur J Appl Physiol*. 2017;117(5):943-953.
30. 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(5):469-477.
31. Duhig SJ, Bourne MN, Buhmann RL, et al. Effect of concentric and eccentric hamstring training on sprint recovery, strength and muscle architecture in inexperienced athletes. *J Sci Med Sport*. 2019;22(7):769-774.
32. Timmins RG, Ruddy JD, Presland J, et al. Architectural changes of the biceps femoris long head after concentric or eccentric training. *Med Sci Sports Exerc*. 2016;48(3):499-508.
33. Pollard CW, Opar DA, Williams MD, Bourne MN, Timmins RG. Razor hamstring curl and Nordic hamstring exercise architectural adaptations: impact of exercise selection and intensity. *Scand J Med Sci Sport*. 2019;29(5):706-715.
34. Hegyi A, Lahti J, Giacomo JP, Gerus P, Cronin NJ, Morin JB. Impact of hip flexion angle on unilateral and bilateral nordic hamstring exercise torque and high-density electromyography activity. *J Orthop Sports Phys Ther*. 2019;49(8):584-592.
35. Ema R, Akagi R, Wakahara T, Kawakami Y. Training-induced changes in architecture of human skeletal muscles: current evidence and unresolved issues. *J Phys Fit Sports Med*. 2016;5(1):37-46.
36. Mjølsnes R, Arnason A, Østhagen T, Raastad T, Bah R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports*. 2004;14(5):311-317.
37. Delahunt E, McGroarty M, De Vito G, Ditroilo M. Nordic hamstring exercise training alters knee joint kinematics and hamstring activation patterns in young men. *Eur J Appl Physiol*. 2016;116(4):663-672.
38. van Dyk N, Witvrouw E, Bahr R. Interseason variability in isokinetic strength and poor correlation with Nordic hamstring eccentric strength in football players. *Scand J Med Sci Sport*. 2018;28(8):1878-1887.
39. Green B, Bourne MN, Pizzari T. Isokinetic strength assessment offers limited predictive validity for detecting risk of future hamstring strain in sport: a systematic review and meta-analysis. *Br J Sports Med*. 2018;52:329-336.

40. Buhmann R, Trajano G, Kerr G, Shield A. Voluntary activation and reflex responses following hamstring strain injury. *Med Sci Sport Exerc* [Internet]. 2020 [cited 2020 Mar 9];1. http://journals.lww.com/10.1249/MSS.0000000000002327

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Marušič J, Vatovec R, Marković G, Šarabon N. Effects of eccentric training at long-muscle length on architectural and functional characteristics of the hamstrings. *Scand J Med Sci Sports*. 2020;30:2130–2142. https://doi.org/10.1111/sms.13770