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High-density electromyography activity in various hamstring exercises

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ABSTRACT

Proximal-distal differences in muscle activity are rarely considered when defining the activity level of hamstring muscles. The aim of this study was to determine the inter-muscular and proximal-distal electromyography (EMG) activity patterns of hamstring muscles during

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common hamstring exercises. Nineteen amateur athletes without a history of hamstring injury performed 9 exercises while EMG activity was recorded along the biceps femoris long head (BFlh) and semitendinosus (ST) muscles using 15-channel high-density electromyography (HD-EMG) electrodes. EMG activity levels normalized to those of a maximal voluntary isometric contraction (%MVIC) were determined for the eccentric and concentric phase of each exercise and compared between different muscles and regions (proximal, middle, distal) within each muscle. Straight-knee bridge, upright hip extension and leg curls exhibited the highest hamstrings activity in both the eccentric (40-54 %MVIC) and concentric phases (69-85 %MVIC). Hip extension was the only BF-dominant exercise (Cohen's d = 0.28 (eccentric) and 0.33 (concentric)). Within ST, lower distal than middle/proximal activity was found in the bent-knee bridge and leg curl exercises (d range = 0.53-1.20), which was not evident in other exercises. BFlh also displayed large regional differences across exercises (d range = 0.00–1.28). This study demonstrates that inter-muscular and proximal-distal activity patterns are exercise-dependent, and in some exercises are affected by the contraction mode. Knowledge of activity levels and relative activity of hamstring muscles in different exercises may assist exercise selection in hamstring injury management.

Keywords: heterogeneous activity; rehabilitation; injury reduction

INTRODUCTION

Hamstring strain is the most frequent injury in sports involving high-speed running [1,2]. For example in football, this type of injury results in a substantial player time loss [1], decreased team performance [3], and significant financial burdens on teams [4]. Re-injury rate can be as high as 24% and is typical in the early stages of return to play [5], suggesting suboptimal loading in the rehabilitation process.

Some interventions implementing eccentric exercises seem to mitigate hamstring injury occurrence [6-10]. In addition to low strength and short muscle length [11,12], neural inhibition [13] and imbalances between the activity level of hamstring muscles [14] are also associated with hamstring injury. Proper exercise selection potentially allows the clinician to better succeed in (re-)injury prevention, but this is challenging for many reasons. For example, non-uniform adaptations to exercise interventions [11,15,16] may be associated with non-uniform hamstring activity patterns across exercises [11,17-19]. Moreover, study results are inconsistent concerning which hamstring muscles are activated in different exercises, as well as the extent of activation [20], and it is questionable whether these differences are real or at least partly reflect the (in)accuracy with which different methods can define muscle activity.

Electromyography (EMG) is the most commonly used method to examine hamstring muscle activity [20]. In conventional EMG studies, electrodes are placed over the mid-belly of hamstring muscles, ignoring possible proximal-distal differences in muscle activity. Studies have shown non-uniform proximal-distal metabolic activity patterns within hamstring muscles [18,19,21]. Similarly, during two common hamstring exercises, we recently observed large differences in muscle activity within the semitendinosus (ST) and biceps femoris long head (BFlh) using high-density EMG (HD-EMG) [22]. Due to such regional differences, spatially robust methods may improve understanding of hamstrings activity patterns. This would potentially allow the clinician to selectively activate specific muscles or muscle regions.

In this study we aimed to define the excitation level of ST and BFlh muscles in the eccentric and concentric phases of 9 typical hamstring exercises. We also tested whether the relative activity of these muscles is similar in the eccentric and concentric phases, as well as if proximal-distal activity patterns are similar across exercises. According to the study aims, exercises were chosen that include clear eccentric and concentric phases (i.e. at the muscle-tendon unit level), and which are generally used in hamstring injury management.

MATERIALS AND METHODS

Participants

Nineteen young male amateur athletes (mean ± standard deviation, age 26.1 ± 3.2 years, body mass 80.2 ± 14.1 kg, height 178.3 ± 9.3 cm) from high injury-risk sports (9 soccer, 6 Gaelic football and 4 rugby players) and experienced at performing hamstring exercises participated in this study. Exclusion criteria were history of hamstring strain, previous anterior cruciate ligament or lower back injury, and cardiovascular or musculoskeletal disorders. Participants received detailed information about the study before they gave written informed consent. Testing procedures were approved by the ethics committee of the University of Jyväskylä and performed according to the Declaration of Helsinki.

Study protocol

The study was performed in the mid-season when the frequency of intense strength training was minimized. Participants refrained from additional strengthening exercises during the study to minimize training effects. Prior to data collection, 12-repetition maximum load

(12RM) was defined for 9 hamstring exercises across 4-5 sessions (4-7 days in-between). The examined exercises were: Good morning (GM), unilateral Romanian deadlift (RDL), cable pendulum (CP), bent-knee bridge (BB), 45° hip extension (45HE), prone leg curl (PLC), slide leg curl (SLC), upright hip-extension conic-pulley (UHC), and straight-knee bridge (SB) (Figure 1 and Video, Supplementary Content). In each session except the last one, 2-3 randomly selected exercises were practiced, then 12RM was tested [23], while exercise technique was assessed and (if needed) corrected by an experienced practitioner to ensure standard technical performance. Unilateral exercises were performed with the dominant (kicking) leg (4 left, 15 right). In the last familiarisation session, maximal voluntary isometric contractions (MVICs) were practiced.

In the main testing session, after preparation and warm-up, participants performed knee flexion and hip extension MVICs for the purpose of EMG normalisation, followed by 6 repetitions of each exercise in a random order. The warm-up consisted of cycling, dynamic stretching (5 minutes each), and then 10 submaximal hip extension and knee flexion contractions performed in a custom-made dynamometer (UniDrive, University of Jyväskylä) [24], with the intensity increasing from ~30 to ~90% MVIC. In the dynamometer where MVICs were performed, participants lay prone with the trunk and hip fixed to the dynamometer bench in neutral position. In the dominant (measured) leg, the knee joint was positioned in 20° of flexion while the other leg was extended. For knee flexion MVICs, the lever arm of the dynamometer was fixed ~5 cm above the lateral malleolus. For hip extension MVICs, the lever arm was strapped just above the knee joint fold, and participants were asked to maintain 20° of knee flexion, which was confirmed before each contraction using a goniometer. For both hip extension and knee flexion MVICs, two repetitions were performed, followed by a third if peak torque differed by > 5% between the first two contractions. For each contraction, maximum effort was maintained for 2 seconds and 2 minutes rest was applied between contractions. A simultaneous performance of knee flexion and hip extension was also performed, wherein the participants reached maximum effort in both tasks simultaneously, which was maintained for 2 seconds. For this task, the dynamometer lever arm was fixed ~5 cm above the lateral malleolus and the thigh was tightly fixed to the bench. Thereafter, 6 repetitions of the 9 selected exercises were performed in random order, at 12 RM load. For the exercises, hip and knee goniometers were aligned with the trochanter major and lateral epicondyle of the femur, respectively. Both the eccentric and concentric phases were performed in 2 seconds, controlled with a metronome. Four minutes rest was applied between exercises. Hip and knee joint angles were recorded as well as BFlh and ST EMG activity. Participants reported no substantial fatigue throughout the testing.

Data collection

To determine correct HD-EMG array positioning, B-mode 2D ultrasonography (Aloka α10, Tokyo, Japan) was used to define and mark the borders of the BFlh and ST muscles as well as the location of their distal musculotendinous junctions. After skin preparation, a 15-channel EMG array (10 mm inter-electrode distance, OT Bioelettronica, Torino, Italy) was secured over each muscle (Figure 2) so that the electrodes were as far away from the muscle borders as possible, to minimize cross-talk. Electrode positioning was standardized so that in BFlh channel 8-9 from the distal end of the array was aligned with the midpoint along the ischial tuberosity – popliteal fossa distance, while in ST the EMG array was placed 1 cm below the tendinous inscription which was located relatively proximally. Arrays were fixed over the skin using adhesive foam and tape. EMG arrays were connected to an amplifier, and signals were digitized (EMG-USB 12-bit A/D converter, OT Bioelectronica) for recording in BioLab software (v3.1, OT Bioelectronica). To maintain skin-electrode contact, electrode cavities were filled with 20 μl conductive gel. A reference electrode was placed over the contralateral wrist. Signal quality was confirmed during submaximal contractions. EMG data were sampled at 2048 Hz and amplified by a factor of 1000. During the measurements, 15 differential channels were recorded from each muscle.

During MVICs, hip extension and knee flexion forces were measured with the dynamometer strain gauge at a sampling frequency of 1000 Hz, digitized (EMG-USB 12-bit A/D converter, OT Bioelectronica) and recorded in BioLab software in synchrony with the EMG signals. Lever arms were measured to calculate torque. For hip extension the lever arm was measured as the distance between the trochanter major and the middle of the strain gauge. For knee flexion the lever arm was measured as the distance between the lateral epicondyle of the femur and the middle of the strain gauge. During muscle contractions, force-time curve feedback was provided.

Hip and knee joint angles were recorded using custom-made electro-goniometers (University of Jyväskylä, Finland). Angle data were digitized by the A/D converter of the EMG system and recorded in BioLab software simultaneously with the EMG data.

Data analysis

A 10-500 Hz fourth-order zero-phase band-pass Butterworth filter was used to filter EMG data in Matlab (MathWorks Inc, Natick, MA, US). For MVICs, root-mean-square (RMS) EMG activity was calculated from a 1-second stable force plateau for each EMG channel. From the exercises, RMS activity was calculated in the entire eccentric and concentric phase (i.e. ~2 seconds for each) for each EMG channel based on hip and knee joint angular displacement. RMS values across the eccentric and concentric phases of the six repetitions were averaged respectively and expressed as a percentage of the highest RMS activity of the corresponding EMG channel during any of the MVIC tasks (%MVIC).

Activity for each muscle was determined for the eccentric and concentric phases separately as the average RMS activity of all 15 channels along the corresponding muscle, which is hereafter referred to as overall activity. To determine the activity level of different muscle regions, average activity was calculated for channels 1-5 (distal region), 6-10 (middle region), and 11-15 (proximal region).

To provide estimates of hip extension and knee flexion strength, maximal torque during the isometric contractions was calculated as the maximum instantaneous force multiplied by the respective lever arm. The highest torque of all repetitions was used for the hip extension and knee flexion tasks.

Statistical analysis

Normal distributions of studentized residuals were confirmed using Shapiro-Wilk test and Q-Q plots. For each exercise and contraction mode, the difference between BFlh and ST overall activity was tested with paired samples t-test in SPSS (IBM, Armonk, NY, USA). Significance level was set at $p < 0.05$. Contraction mode*region interaction for each exercise and region*exercise interactions for each contraction mode were tested for each muscle with repeated-measures ANOVA. If Mauchly's test of sphericity was violated ($p<0.05$), Greenhouse-Geisser adjustment was applied. Differences were located after Bonferroni correction. Cohen's *d* ±90% confidence intervals (90% CI) were calculated to determine the magnitude of differences using a custom spreadsheet [25]. Differences were considered as trivial (<0.2), small (≥0.2), moderate (≥0.5), or large (≥0.8). Differences where 90% CIs overlapped both 0.2 and -0.2 were considered unclear [26].

RESULTS

Maximal hip extension and knee flexion torque during the isometric contractions were 236.5 ± 84.1 Nm and 153.3 ± 59.2 Nm (mean ± standard deviation), respectively.

Overall activity

BFlh overall activity level ranged across exercises from an average of 17% to 54% in the eccentric, and 32% to 83% in the concentric phase, relative to MVIC (Figure 3). In ST, activity levels of 19% to 51% in the eccentric and 33% to 85% in the concentric phase were observed (Figure 3).

The only exercise with higher activity in BFlh compared to ST was 45HE: in both the concentric and eccentric phases, small differences between muscles were found ($d = 0.28 \pm 0.28$ and 0.33 ± 0.24, respectively), which reached statistical significance in the concentric but not the eccentric phase ($p = 0.026$ and 0.100, respectively). ST activity was higher than BFlh activity in the eccentric phase of GM ($d = 0.21 \pm 0.19$) and concentric phase of PLC, SLC and BB exercises ($d = 0.35 \pm 0.27$, 0.26 ± 0.28, and 0.24 ± 0.25, respectively), from which only PLC reached statistical significance ($p = 0.036$, 0.118, and 0.107, respectively). Between-muscle differences are presented in Table 1.

Regional activity patterns

Mean and standard deviation of regional activity levels are shown in Figure 4. Different exercises showed distinct regional patterns both in ST ($p < 0.001$ in both eccentric and concentric) and in BFlh (eccentric: $p = 0.001$, concentric: $p < 0.001$). The contraction mode affected the regional activity pattern of ST in BB, HE, PLC and SLC ($p = 0.001$, $p = 0.040$, $p < 0.001$, and $p < 0.001$, respectively), and the regional activity pattern of BFlh in UHC, PLC, SB and SLC ($p = 0.012$, $p < 0.001$, $p = 0.016$ and $p = 0.009$, respectively).

Lower activity in the distal compared to the middle or proximal regions was found in BB, PLC and SLC (*d* range = 0.53 – 1.20, $p < 0.05$), in both the eccentric and concentric phases. In all other exercises, no or only small differences between distal vs other regions were found (*d* range = 0.00 – 0.40, $p > 0.05$). Similarly in BFlh, a large range in the magnitude of regional differences was observed across exercises (difference between regions, *d* range = 0.02 – 1.28), with PLC displaying the largest differences between muscle regions (*d* range = 0.41 – 1.28). Differences are detailed in Table 2.

DISCUSSION

In the current study, muscle activity patterns were determined in 9 typical hamstring exercises using HD-EMG while taking proximal-distal differences into account. Small differences between the activity levels of BFlh and ST muscles were observed in the concentric phase of 45HE, SLC, PLC and BB, from which the only BFlh-dominant exercise- 45HE- showed a difference in the eccentric phase. Proximal-distal distribution of EMG signals varied substantially across exercises, and showed different patterns between ST and BFlh muscles.

In addition to recent studies using muscle functional magnetic resonance imaging (mfMRI) [18,19,21] and our previous results using HD-EMG [22], the exercise-dependent changes in proximal-distal activity patterns observed in this study reinforce the notion that spatially robust methods are needed to accurately describe the activity level of ST and BFlh muscles. This is further supported by the substantially different proximal-distal EMG activity patterns between muscles in most of the exercises. This was most pronounced in BB, wherein regional differences were moderate-to-large in ST but trivial in BFlh. This phenomenon likely leads to a non-systematic error when the activity levels of these muscles are compared based on a small region of the muscle.

Similar to previous studies [17,27], we found high normalized activity levels in SB, SLC and PLC. Additionally, during UHC, which has not been the focus of many experiments, the activity level exceeded 80 %MVIC in the concentric phase. High activity levels in these exercises may facilitate training-induced adaptations in the hamstrings, although adaptations in response to these exercises are unclear. In accordance with previous literature [28], particularly low overall hamstrings activity was observed in GM, which is apparently associated with low hamstring muscle forces in this exercise [29]. Exercises inducing limited hamstrings activity are likely suboptimal to facilitate meaningful muscle adaptations.

The relevance of the relative roles of individual hamstring muscles in hamstring injury are yet to be clarified. Training interventions should target the mitigation of injury risk factors. An imbalance between BFlh and ST muscle activity level seems to be associated with hamstring injuries [14]. Thus, balanced strengthening of these muscles should be a training goal. Although conventional EMG studies are not in agreement, previous mfMRI studies suggest that BFlh is relatively more active in hip-dominant exercises, while ST is relatively more active in knee-dominant exercises [20]. Based on the current study, it seems rather challenging to preferentially activate BFlh. Previously, mfMRI showed relatively high activity in BFlh compared to ST in 45HE [17], which is confirmed by our results. Other hip-dominant exercises did not induce higher activity in BFlh than in ST in this study.

Contraction-mode dependent between-muscle activity patterns were observed in some exercises in the current study. In the concentric phase, three exercises - SLC, PLC and UHC - showed higher activity in ST compared to BFlh. However, this difference was not evident in the eccentric phase of these exercises. This is inconsistent with previous results concerning eccentric PLC (120% concentric 1RM) [18,30] and the mechanically similar high-load eccentric-only Nordic hamstring exercise [17,22,31], which seem to selectively activate ST. This discrepancy may be explained by the substantially lower load applied in the current study. Similar to these exercises, no between-muscle differences were found in the eccentric phase of SB, BB or one-leg RDL. Based on the current study, these exercises should be used when balanced eccentric activation of ST and BFlh muscles is of interest. However, it is also likely important to include exercises with a relatively high overall hamstrings activity level to better facilitate muscle adaptations. The above observations suggest that ST-BFlh muscle selectivity cannot always be predicted based solely on the hip- or knee-dominant nature of the exercise, and may be affected by different neural control strategies in the eccentric and concentric phases.

In BFlh, eccentric stimuli may be of particular importance to elicit fascicle lengthening, which seems to reduce the risk for hamstring injury [12]. 45HE exhibited the largest activity in BFlh relative to ST, and has already been shown to effectively increase BFlh fascicle length [11]. Although activity level was higher in SB, UHC, SLC and PLC in our study, this does not necessarily imply that the eccentric phase of these exercises can more effectively elongate BFlh fascicles. Askling et al. [7,8] demonstrated that exercises performed at longer muscle operating lengths are more effective for injury prevention than those requiring hamstrings to operate at a shorter length. Muscle length is clearly longer in 45HE compared to all four of the aforementioned high-activity exercises. Nonetheless, Nordic hamstring exercise also seems to reduce hamstring injuries [6,9,10], even though the operating length is likely similar to that in SLC and PLC. Future studies should further clarify which of these exercises are the most beneficial to mitigate injury risk factors.

During rehabilitation, it may be of value to know regional activity patterns relative to the injury site to enable selective activation of the injured muscle region. In 80% of running-type hamstring injuries, the BFlh is affected primarily, and typically at the proximal site [32]. Within the BFlh, the proximal region seems to be the most challenging to activate since this region did not show higher activity compared to the distal or middle regions in any of the exercises in the current study. On the contrary, lunge [19] and CP [21]have been shown to activate the proximal BFlh in mfMRI studies. In the current study, CP showed the lowest activity in the proximal region. In any case, in both lunge [33] and CP, the overall hamstrings activity level is rather low, likely limiting meaningful adaptations in response to these exercises. Manipulating the shin angle during a lunge may expose the hamstrings to substantially higher forces [29], likely increasing hamstrings activity. However, it is unclear whether this manipulation alters the proximal-distal activity pattern. Future studies should examine whether targeting the injured muscle region during the rehabilitation process accelerates the restoration of muscle function after a hamstring injury.

It should be mentioned that some discrepancies exist when comparing some of our results with some previous mfMRI findings. Contrary to our finding that there are only trivial differences between ST and BFlh muscle activity levels in RDL, this exercise has been suggested to be a BFlh-dominant exercise based on mfMRI data [34]. However, in that study, the exercise was performed bilaterally and included only 6 participants. In any case, in our study, hamstrings activity levels were 21% and 43% in the eccentric and concentric phases of RDL, the second lowest out of the examined exercises, likely minimizing the clinical relevance of this difference. On the contrary, hamstrings activity was particularly high in SB. In the current study, we did not detect clear differences between muscles in SB, contrary to Bourne et al. [35] who found higher metabolic activity in ST compared to BFlh, although the between-muscle difference seems to be smaller compared to most of the other exercises previously examined with mfMRI [20]. These discrepancies may arise from methodological issues: both mfMRI and EMG have limitations when comparing the relative contribution of different hamstring muscles. Metabolic activity estimated by mfMRI is sensitive to glycolysis [36], vascular dynamics [37] and fiber type proportions [38], which may differ between muscles and individuals. With respect to EMG, it is not clear whether reference contractions used for normalization activate all examined hamstring muscles to a similar extent. Accordingly, to examine the relative contribution of different hamstring muscles using these methods, it is likely most appropriate to compare within the same individuals and measurement session across exercises.

As a possible limitation of this study, surface EMG is prone to cross-talk. To minimize this effect, we used HD-EMG electrodes with a relatively shallow pick-up area and 10 mm inter-electrode distance [39], ensured correct electrode location using ultrasonography, and measured male athletes with a relatively thin subcutaneous layer overlying the target muscles. Furthermore, recording from 15 cm along each muscle likely minimized the effect of muscle movement relative to the skin, which is considered an inherent limitation of surface EMG. Additionally, muscle regions were covered to a slightly different extent across individuals due to differences in muscle length relative to the length of the EMG arrays. As an additional limitation, we measured amateur athletes without a history of hamstring injury, so our results may not be directly applicable to other populations, e.g. injured and/or professional athletes.

PERSPECTIVES

HD-EMG revealed exercise-specific inter- and intramuscular hamstring activity patterns in 9 typical hamstring exercises. This study also revealed that the relative activity of different hamstring muscles may differ between the eccentric and concentric phases of an exercise. These findings highlight the potential impact of exercise selection procedure on hamstrings strengthening. The clinical implications of heterogeneous hamstrings EMG activity should be further examined, as well as the mechanisms and functional relevance of heterogeneous activity.

CONFLICT OF INTEREST

The authors have no professional relationships with any company or manufacturer who would benefit from the current study results.

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FIGURE CAPTIONS

Figure 1: Examined hamstring exercises

Figure 2: High-density electromyography (HD-EMG)

Figure 3: Overall activity levels based on 15-channel arrays

Figure 4: Hamstrings regional EMG activity patterns

FIGURE LEGENDS

Figure 1. Nine typical rehabilitation exercises examined in this study. GM, Good morning; RDL, Unilateral Romanian deadlift; CP, Cable pendulum; BB, Bent-knee bridge; 45HE, 45° hip extension; PLC, Prone leg curl; SLC, Slide leg curl; UHC, Upright hip extension conic-pulley; SB, Straight-knee bridge.

Figure 2. High-density electromyography (HD-EMG) arrays (A) were attached and secured (B) over the semitendinosus (ST) and the long head of the biceps femoris (BFlh) to comprehensively describe muscle activity level during each exercise.

Figure 3. Electromyography (EMG) activity levels in the eccentric (A) and concentric (B) phase of each exercise. Mean and standard deviation are presented. Data represent the average of 15 EMG channels along each muscle. Dotted lines represent equal activity level between the two muscles when normalized to maximal voluntary isometric activity (MVIC). GM, Good morning; RDL, Unilateral Romanian deadlift; CP, Cable pendulum; BB, Bent-knee bridge; 45HE, 45° hip extension; PLC, Prone leg curl; SLC, Slide leg curl; UHC, Upright hip extension conic-pulley; SB, Straight-knee bridge.

Figure 4. Mean and standard deviation of the normalized activity level (%MVIC, maximal voluntary isometric contraction) in the proximal, middle and distal regions of each muscle during the eccentric and concentric phase of each exercise. GM, Good morning; RDL, Unilateral Romanian deadlift; CP, Cable pendulum; BB, Bent-knee bridge; 45HE, 45° hip extension; PLC, Prone leg curl; SLC, Slide leg curl; UHC, Upright hip extension conic-pulley; SB, Straight-knee bridge.

Table 1. Differences (Cohen's d ± 90% confidence limits) between BFlh and ST muscles in the eccentric and concentric phase of hamstring exercises.

	Eccentric		Concentric	
Straight-knee bridge (SB)	0.19	±0.37[T]	-0.09	±0.36[U]
Upright hip extension conic-pulley (UHC)	0.11	±0.33[U]	-0.16	±0.29[T]
Slide leg curl (SLC)	0.12	±0.25[T]	-0.26	±0.28[S]
Prone leg curl (PLC)	0.17	±0.20[T]	-0.35	±0.27[S]
45° hip extension (45HE)	0.28	±0.28[S]	**0.33**	**±0.24[S]**
Bent-knee bridge (BB)	-0.17	±0.27[T]	-0.24	±0.25[S]
Cable pendulum (CP)	-0.02	±0.43[U]	0.01	±0.38[U]
Unilateral Romanian deadlift (RDL)	-0.19	±0.24[T]	-0.11	±0.22[T]
Good morning (GM)	-0.21	±0.19[S]	-0.09	±0.25[T]

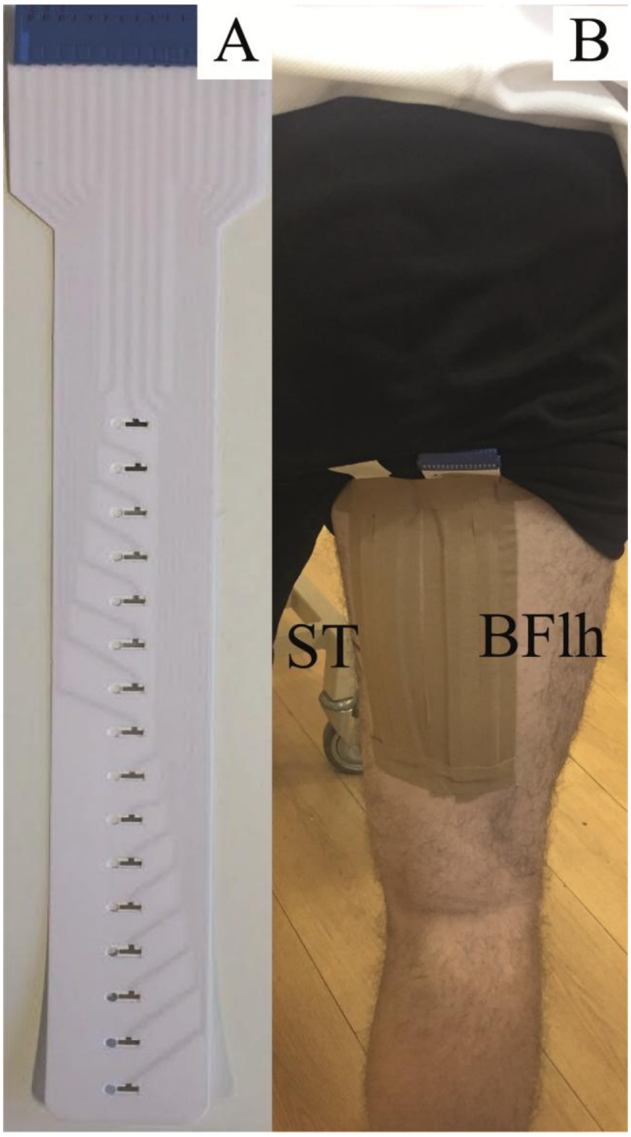
Positive values: biceps femoris long head > semitendinosus (BFlh > ST)
Negative values: biceps femoris long head < semitendinosus (BFlh < ST)
T = trivial difference, S = small difference between muscles, U = unclear. **p<0.05**

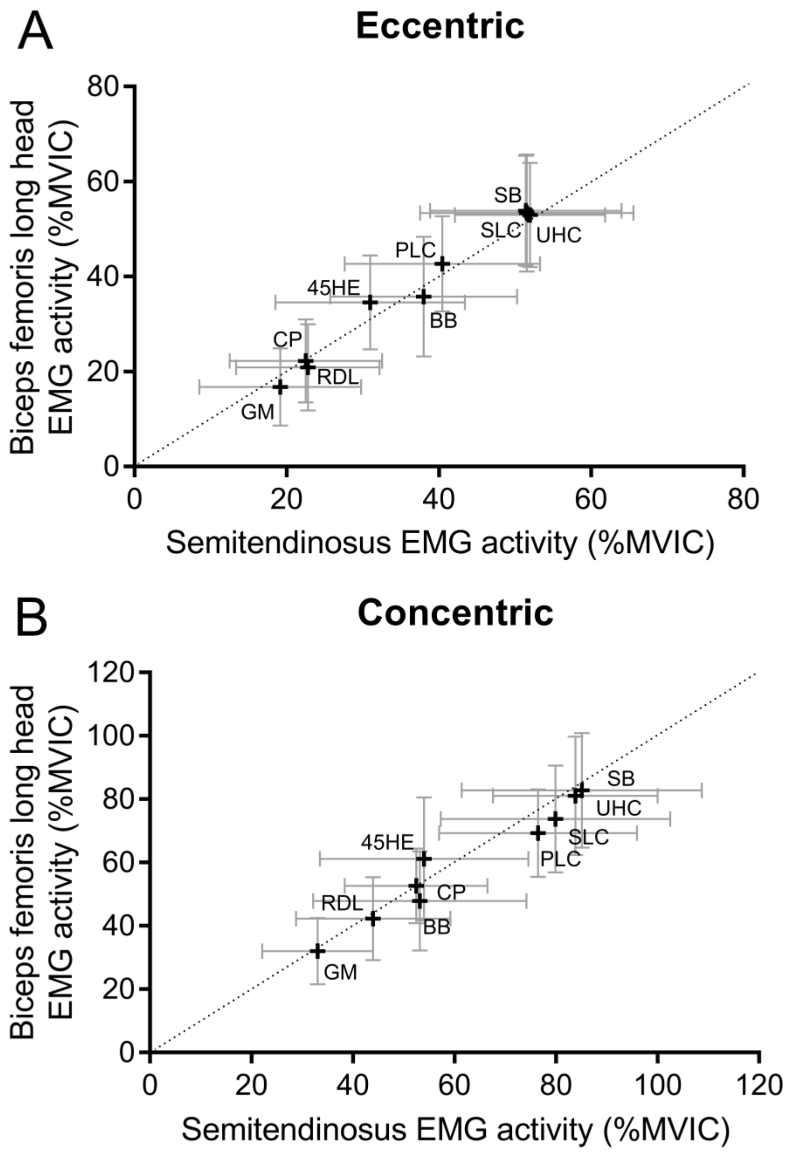
Table 2. Regional differences in the electromyography activity level of hamstring muscles in the eccentric and concentric phase of hamstring exercises.

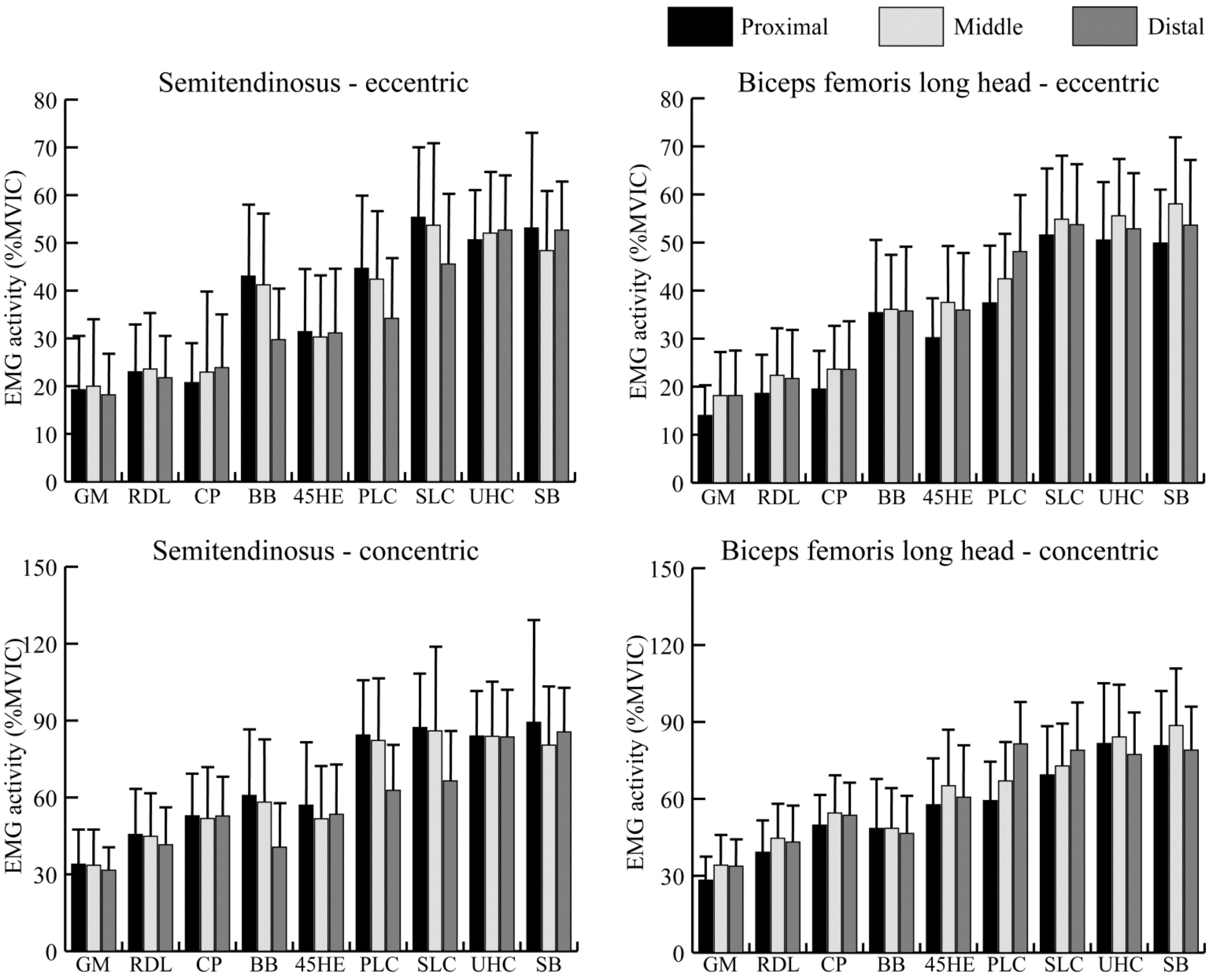
	Eccentric								Concentric							
	Semitendinosus				Biceps femoris long head				Semitendinosus				Biceps femoris long head			
Region	middle		proximal		middle		proximal		middle		proximal		middle		proximal	
	Straight-knee bridge (SB)															
distal	-0.40	±0.42^{S}	0.04	±0.67^{U}	0.31	±0.24^{S}	-0.26	±0.32^{S}	-0.29	±0.39^{S}	0.21	±0.79^{U}	**0.54**	**±0.31^{M}**	0.10	±0.44^{U}
middle	–		0.44	±0.43^{S}	–		**-0.58**	**±0.27^{M}**	–		0.50	±0.59^{M}	–		-0.45	±0.33^{S}
	Upright hip extension conic-pulley (UHC)															
distal	-0.06	±0.41^{U}	-0.17	±0.34^{T}	0.22	±0.19^{S}	-0.19	±0.30^{T}	0.01	±0.40^{U}	0.02	±0.38^{U}	**0.40**	**±0.23^{S}**	0.25	±0.41^{S}
middle	–		-0.12	±0.30^{T}	–		**-0.42**	**±0.26^{S}**	–		0.01	±0.33^{U}	–		-0.15	±0.34^{T}
	Slide leg curl (SLC)															
distal	**0.53**	**±0.33^{M}**	**0.63**	**±0.32^{M}**	0.09	±0.23^{T}	-0.16	±0.28^{T}	**0.95**	**±0.43^{L}**	**1.02**	**±0.32^{L}**	-0.31	±0.26^{S}	**-0.49**	**±0.28^{S}**
middle	–		0.11	±0.30^{T}	–		-0.25	±0.25^{S}	–		0.07	±0.41^{U}	–		-0.18	±0.20^{T}
	Prone leg curl (PLC)															
distal	**0.62**	**±0.29^{M}**	**0.79**	**±0.31^{M}**	**-0.46**	**±0.28^{S}**	**-0.87**	**±0.30^{L}**	**1.03**	**±0.28^{L}**	**1.15**	**±0.30^{L}**	**-0.84**	**±0.32^{L}**	**-1.28**	**±0.30^{L}**
middle	–		0.17	±0.30^{T}	–		**-0.41**	**±0.20^{S}**	–		0.11	±0.39^{U}	–		**-0.45**	**±0.24^{S}**
	45° hip extension (45HE)															
distal	-0.06	±0.22^{T}	0.02	±0.23^{U}	0.13	±0.18^{T}	**-0.46**	**±0.28^{S}**	-0.08	±0.24^{T}	0.17	±0.26^{T}	0.21	±0.17^{S}	-0.14	±0.24^{T}
middle	–		0.08	±0.18^{T}	–		**-0.59**	**±0.23^{M}**	–		0.26	±0.19^{S}	–		-0.35	±0.23^{S}
	Bent-knee bridge (BB)															
distal	**1.03**	**±0.34^{L}**	**1.20**	**±0.44^{L}**	0.02	±0.21^{T}	-0.02	±0.22^{U}	**0.98**	**±0.30^{L}**	**1.13**	**±0.37^{L}**	0.13	±0.23^{T}	0.13	±0.27^{T}
middle	–		0.16	±0.44^{U}	–		-0.05	±0.26^{U}	–		0.14	±0.37^{U}	–		0.00	±0.30^{U}
	Cable pendulum (CP)															
distal	-0.08	±0.47^{U}	-0.27	±0.36^{S}	0.00	±0.14^{T}	**-0.39**	**±0.18^{S}**	-0.06	±0.45^{U}	0.00	±0.42^{U}	0.07	±0.25^{T}	-0.28	±0.35^{S}
middle	–		-0.19	±0.53^{U}	–		**-0.39**	**±0.15^{S}**	–		0.06	±0.44^{U}	–		-0.35	±0.34^{S}
	Unilateral Romanian deadlift (RDL)															
distal	0.20	±0.36^{S}	0.14	±0.30^{T}	0.06	±0.13^{T}	**-0.29**	**±0.17^{S}**	0.21	±0.32^{S}	0.26	±0.32^{S}	0.10	±0.14^{T}	-0.26	±0.19^{S}
middle	–		-0.06	±0.24^{T}	–		**-0.35**	**±0.13^{S}**	–		0.05	±0.26^{U}	–		**-0.36**	**±0.18^{S}**
	Good morning (GM)															
distal	0.20	±0.42^{U}	0.12	±0.33^{U}	0.00	±0.13^{T}	**-0.42**	**±0.18^{S}**	0.21	±0.42^{U}	0.25	±0.48^{U}	0.04	±0.14^{T}	**-0.47**	**±0.17^{S}**
middle	–		-0.08	±0.25^{T}	–		**-0.42**	**±0.14^{S}**	–		0.05	±0.40^{U}	–		**-0.51**	**±0.20^{M}**

Cohen's *d* ±90% confidence limits. T = trivial difference, S = small difference, M = moderate difference, L = large difference between regions, U = unclear. Positive and negative differences correspond to higher activity level in the relatively more proximal and distal regions, respectively. **$p<0.05$**


GM
45HE
PLC
SB
RDL
BB
UHC
SLC
CP


A
B
ST
BFlh


A
Eccentric
Biceps femoris long head EMG activity (%MVIC)
Semitendinosus EMG activity (%MVIC)
0
20
40
60
80
SB
SLC
UHC
PLC
45HE
BB
CP
RDL
GM
B
Concentric
Biceps femoris long head EMG activity (%MVIC)
Semitendinosus EMG activity (%MVIC)
0
20
40
60
80
100
120
SB
UHC
SLC
PLC
45HE
CP
RDL
BB
GM



Proximal
Middle
Distal
Semitendinosus - eccentric
Biceps femoris long head - eccentric
Semitendinosus - concentric
Biceps femoris long head - concentric
EMG activity (%MVIC)
GM
RDL
CP
BB
45HE
PLC
SLC
UHC
SB