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Title: Region-dependent hamstrings activity in Nordic hamstring exercise and stiff-leg deadlift defined with high-density electromyography

Year: 2018

Version:

Please cite the original version:

Hegyi, A., Peter, A., Finni Juutinen, T., & Cronin, N. (2018). Region-dependent hamstrings activity in Nordic hamstring exercise and stiff-leg deadlift defined with high-density electromyography. Scandinavian Journal of Medicine and Science in Sports, 28(3), 992-1000. https://doi.org/10.1111/sms.13016

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Article type : Original Article

Title: Region-dependent hamstrings activity in Nordic hamstring exercise and stiff-leg deadlift defined with high-density EMG

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Running head: Regional hamstring activity in NHE and SDL

ABSTRACT

Recent studies suggest region-specific metabolic activity in hamstring muscles during injury prevention exercises, but the neural representation of this phenomenon is unknown. The aim of this study was to examine whether regional differences are evident in the activity of biceps femoris long head (BFlh) and semitendinosus (ST) muscles during two common injury prevention exercises. Twelve male participants without a history of hamstring injury performed the Nordic hamstring exercise (NHE) and stiff-leg deadlift (SDL) while BFlh and ST activity were recorded with high-density electromyography (HD-EMG). Normalised activity was calculated from the distal, middle, and proximal regions in the eccentric phase of each exercise. In NHE, ST overall activity was substantially higher than in BFlh ($d = 1.06$ ±0.45), compared to trivial differences between muscles in SDL ($d = 0.19$ ±0.34). Regional differences were found in NHE for both muscles, with different proximo-distal patterns: the distal region showed the lowest activity level in ST (regional differences, *d* range = 0.55 – 1.41) but the highest activity level in BFlh (regional differences, *d* range = 0.38 – 1.25). In SDL, regional differences were smaller in both muscles (*d* range = 0.29 – 0.67 and 0.16 – 0.63 in ST and BFlh, respectively) than in NHE. The use of HD-EMG in hamstrings revealed heterogeneous hamstrings activity during typical injury prevention exercises. High-density EMG might be useful in future studies to provide a comprehensive overview of hamstring muscle activity in other exercises and high-injury risk tasks.

Keywords: electrical activity, bi-articular hamstrings, muscle function

INTRODUCTION

Hamstring injuries are the most common in sports involving high-speed running[1-3]. Optimising hamstring exercise selection for prevention of and rehabilitation from hamstring injury is of major interest since low eccentric strength is thought to be one of the most significant[4-6] but modifiable[7-10] risk factors for hamstring injury. In recent decades, injury incidence has not decreased[11], highlighting the need for studies examining the possible mechanisms of injury.

Bi-articular components of the hamstrings (biceps femoris long head (BFlh), semitendinosus (ST) and semimembranosus) contribute to both hip extension and knee flexion[12]. Thus, complex within-muscle hamstring coordination may be required. Recent studies using muscle functional magnetic resonance imaging (mfMRI) suggest that hamstring exercises may cause heterogeneous elevation of transverse (T2) relaxation time within different hamstring muscles, implying inhomogeneous metabolic activity of different muscle regions[13,14]. However, there is a lack of information about the neural representation of this phenomenon. Additionally, mfMRI cannot be used in real-time. Therefore, other methods of defining muscle activity are needed to comprehensively understand hamstring muscle function. Electromyography (EMG) has been widely used to define real-time ST and BFlh activity in a variety of hamstring exercises[15-18], but has relied on a single pair of EMG electrodes placed over each muscle. Assuming that the aforementioned mfMRI changes are reflected in the EMG activity, conventional EMG configurations may not be sufficient to describe overall muscle activity accurately.

High-density surface electromyography (HD-EMG) has been used recently to provide a more comprehensive overview of human muscle activity[19]. This method has revealed regional differences (e.g. proximal vs. distal) in the activity of different muscles during stimulation and voluntary movements, e.g. walking[20-23]. The method has not yet been used in hamstrings, but would likely provide further insights to hamstring activity during strengthening exercises. Recent mfMRI studies suggest that hip-dominant exercises may activate proximal BFlh preferentially, while in knee-dominant exercises distal BFlh is relatively more activated[14,24], which may be of interest from an injury prevention perspective. Thus in this study, to examine whether heterogeneous activity of hamstring regions exists, two exercises which are frequently used in injury prevention - the knee-dominant Nordic hamstring exercise (NHE) and the hip-dominant stiff-leg deadlift (SDL) - were investigated with HD-EMG. We aimed to examine the eccentric-only NHE and the eccentric phase of SDL to avoid contraction mode bias. We hypothesised that differences would be observed between normalised EMG activity of the proximal, middle and distal regions of BFlh and ST during NHE and SDL.

MATERIALS AND METHODS

Participants

Twelve recreationally active young males (age 24.3 ± 3.7 years, body mass 74.2 ± 8.3 kg, height 179.3 ± 8.8 cm) with weightlifting experience and without any cardiovascular or musculoskeletal disorders volunteered for this study. Participants had no known history of hamstring injury, or any lower extremity/lower back injuries in the past 3 years. After informing the participants about the study details, they gave written consent before data collection. Testing procedures were approved by the ethics committee of the University of Jyväskylä and performed in accordance with the Declaration of Helsinki.

Study design

In the familiarisation session (10-14 days before the testing), 1 repetition maximum (1RM) was defined for SDL[25]. Participants also practiced the NHE, and maximal voluntary isometric contractions (MVICs) with visual force-time curve feedback.

In the main testing session, after preparation and warm-up, participants lay prone in a custom-made dynamometer (UniDrive, University of Jyväskylä)[26] with hip joint and trunk fixed to the dynamometer bench in neutral position. For EMG signal normalisation, participants performed maximal hip extension and knee flexion MVICs after a specific warm-up including ten submaximal contractions with increasing intensity (from ~30 to ~90%). Activity along the BFlh and ST muscles was recorded during MVICs using HD-EMG arrays (Figure 1). During knee flexion contractions, the knee joint was fixed at ~20 degrees of flexion while the lever arm of the dynamometer was strapped 2 cm above the lateral malleolus. During hip extension, participant positioning was identical but the lever arm of the dynamometer was fixed 1 cm above the knee fold. Participants were asked to perform hip extension with a slightly flexed knee to match the position in the knee flexion tasks. Three maximal contractions were performed and maintained for 2 seconds for both knee flexion and hip extension (2 minutes rest in-between). Knee flexion or hip extension alone were assumed to be insufficient to evoke maximal muscle activity in all EMG channels. Thus, participants also performed hip extension MVICs superimposed on knee flexion MVICs (3 reps, 2 minutes rest in-between). In this task, the cuff of the dynamometer lever arm was fixed 2 cm above the lateral malleolus, and the thigh was strapped to the bench above the knee fold. Participants started by increasing knee flexion then adding hip extension, reaching maximal effort in both tasks in ~2 seconds and maintaining it for another 2 seconds. Thereafter, NHE and SDL exercises were performed in random order.

Exercise description

Nordic hamstring exercise

The knee-dominant NHE (5 repetitions, 2-min rest in-between) was performed on a custom-made device with force transducers attached above the ankles[27]. Participants started from a kneeling position, with arms crossed in front of the body. They then lowered the body forward as far as possible at a constant speed of 18 ° s^{-1} controlled with a metronome. The hips and torso were in neutral position throughout the range of motion. NHE was performed as a bodyweight-only exercise, and participants were not able to resist until full knee extension. Force from each leg and EMG activity along the ST and BFlh were recorded during the exercise (Supplementary video 1).

Stiff-leg deadlift

In the hip-dominant SDL, the starting position was upright. Throughout the range of motion, the knees were straight but not locked, and the back was in neutral position with closed scapulae. Participants lowered the bar close to the body towards the floor until the plates touched the floor or for as long as proper technique could be maintained. In the upward movement, the hips were extended to the starting position. The downward and upward movements were each performed in 2 seconds. Five repetitions were performed at 80% 1RM, with 2-min rest between repetitions. Joint kinematics and EMG activity along the muscles were recorded during the exercise (Supplementary video 2).

Data collection

EMG

HD-EMG preparation was performed while participants lay prone with neutral hip and knee joint angles. The right leg was measured for every participant. To determine proper HD-EMG array positioning, BFlh and ST muscle borders were determined with B-mode 2D ultrasonography (Aloka α10, Tokyo, Japan) and the skin over the borders was marked with a pen. After skin preparation, 15-channel semi-disposable EMG arrays (OT Bioelettronica, Torino, Italy) were attached along the midline between the borders for each muscle using adhesive foam, and connected to the amplifier of the EMG system. The cavities of the electrode arrays were filled with 20 µl conducting gel for proper electrode-skin contact (Figure 1). Electrode arrays were further secured with adhesive tape to minimise movement artefact. For BFlh, channel eight/nine from the distal end of the array was aligned with the midpoint on the line between the ischial tuberosity and knee joint fold. For ST, the array was attached below the tendinous inscription[28] of the muscle defined with ultrasonography. A reference electrode was placed over the left wrist. Signal quality was checked during submaximal knee flexion contractions. EMG data were sampled at 2048 Hz, amplified (x1000) and digitised (EMG-USB 12-bit A/D converter, OT Bioelectronica). During each task, 15 differential signals were recorded from each muscle using BioLab software (v3.1, OT Bioelectronica).

Kinematics

Before performing the exercises, reflective markers (14 mm diameter) were secured over the anterior and posterior superior iliac spine, lateral thigh, lateral epicondyle of the femur, lateral shank, lateral malleolus, calcaneus and second metatarsal head of each side, to determine hip and knee joint angular displacements. 3D marker displacements were recorded using an 8-camera motion analysis system sampling at 250 Hz in Nexus software (Vicon Motion Systems Inc., Oxford, UK).

Force

MVIC and NHE force data (strain gauge at the ankle, see supplementary video 1) were collected at 1000 Hz and digitised using an A/D converter (Cambridge Electronic Design, Cambridge, UK), and recorded in Spike2 software (Cambridge Electronic Design). Force and EMG data were synchronised by sending a pulse from Spike2 to the EMG software. Spike2 software was also used to send a digital pulse to the Nexus software to synchronise EMG and kinematic data.

Data analysis

As NHE is an eccentric-only exercise, muscle activity levels were determined in the eccentric phase of each task to make exercises comparable. For NHE, force measured from the right leg was used to determine the active lengthening phase: from the start of force increment to the instant of peak force. For SDL, the eccentric phase was defined based on muscle-tendon length change: hip and knee joint angular displacements were calculated in Nexus software based on the Plug-in Gait Model after smoothing marker trajectories with an 8 Hz low-pass Butterworth filter. Joint angular data were then imported to Matlab (MathWorks Inc, Natick, MA, US), where ST and BFlh muscle-tendon lengths were calculated using modelling equations[29].

EMG data were band-pass filtered using a 10-500 Hz fourth-order zero-phase Butterworth filter in Matlab. For MVICs, root-mean-square (RMS) EMG was calculated from a 1-second stable plateau for each EMG channel. In NHE and SDL, RMS activity in the eccentric phase (defined as above) was calculated. RMS values across repetitions were averaged for each exercise and expressed as a percentage of the highest RMS activity of the corresponding channel during any of the MVIC tasks (%MVIC). Channels 1-5, 6-10, and 11-15 were then averaged to represent activity in the distal, middle and proximal regions, respectively. Overall activity was defined as the average normalised RMS activity of all 15 channels for each muscle. This approach minimised the effects of muscle shift under the skin on regional EMG activity.

Statistical analysis

The magnitude of the differences (Cohen's *d* ±90% confidence limits) between the overall activity levels of ST and BFlh muscles, and regional activity within each muscle in NHE and SDL were calculated using a custom spreadsheet[30]. Differences were classified as trivial (<0.2), small (≥0.2), moderate (≥0.5), or large (≥0.8). Nonetheless, differences with 90% confidence intervals overlapping both the positive (≥0.2) and negative (≤-0.2) smallest worthwhile standardized effects were deemed to be unclear effects[31].

RESULTS

Peak NHE force was 285 ± 48 N; load for SDL was 86.9 ± 25.8 kg (mean ± standard deviation). Figures 2 and 3 represent group average normalised activity for each EMG channel during NHE and SDL, respectively. Regional EMG activities for each individual are illustrated in Figure 4.

During NHE, activity within ST was highest in the middle region (80.48 ± 13.78 %MVIC), and differences between regions were substantial (*d* range = 0.55 to 1.41). BFlh activity was highest in the distal region (72.08 ± 10.66 %MVIC) and lowest in the proximal region (57.74 ± 15.95 %MVIC), with small to large differences between regions (*d* range = 0.38 to 1.25). In SDL, ST activity was highest in the middle region (40.70 ± 9.44 %MVIC), and differences between regions were small to moderate (*d* range = 0.29 to 0.67). In BFlh, the proximal region displayed the lowest activity level (32.23 ± 8.55 %MVIC) and the difference between the middle and distal regions was trivial (*d* = 0.16 ±0.27). All within-muscle comparisons are shown in Table 1.

With respect to overall activity, ST presented substantially higher activity than BFlh in NHE (72.31 ± 7.33 %MVIC vs. 63.97 ± 10.46 %MVIC, *d* = 1.06 ±0.45), but in SDL the difference between muscles was negligible (37.46 ± 6.74 %MVIC in ST vs. 36.07 ±8.54 %MVIC in BFlh, *d* = 0.19 ±0.34).

DISCUSSION

This study has shown using HD-EMG that intramuscular distribution of normalised EMG activity is non-uniform along the BFlh and ST muscles; the middle-to-proximal region of ST and the distal region of BFlh showed the highest within-muscle activity, irrespective of exercise. Regarding inter-muscular differences, higher activity was observed in ST compared to BFlh in NHE, but no differences between muscles were observed in SDL.

Region-specific muscle activity

In BFlh, the region effect was larger in NHE than in SDL, with large and moderate effects, respectively. In both tasks, the distal region was activated the most. This is consistent with preferentially distal BFlh muscle use based on mfMRI studies in NHE[32], and in the mechanically similar eccentric knee extension task[13]. However, rather homogeneous muscle metabolic activity was previously found in a modified SDL[14], contrary to our study wherein differences between regions were present, though smaller compared to NHE.

In ST, large differences in activity between regions were detected during NHE, whereby the middle and proximal regions were more active than the distal region. Similarly, in a previous study, middle and proximal regions of ST were more active than the distal region in eccentric knee extension[13]. Another previous study found that the middle region showed the highest activity in a modified SDL[14], in accordance with the current study.

Abundant innervation of BFlh and ST likely contributes to the region-specific activity of these muscles. One-to-three primary nerves innervating different BFlh regions divide into two or more primary branches[28,33] that may contribute to region-dependent activity. ST muscle is divided into upper and lower parts by a tendinous inscription, which is an attachment zone for most of the fascicles proximally and distally[28]. Both parts are innervated by a separate primary motor nerve implying separate function of regions. In this study, activity was recorded from below the tendinous inscription due its relatively proximal location. ST showed heterogeneous distribution of muscle activity within this part. Small territories of motor units may be responsible for independent activity of hamstring muscle regions, which is yet to be examined.

In other muscles, e.g. in biceps brachii, region-specific activity has been linked to non-uniform hypertrophy after a training intervention[34]. Accordingly, ST is the thickest in the upper mid-region, which is the region where the highest activity was found in our study. On the contrary, BFlh showed the highest activity in the distal region where muscle thickness is lower compared to the middle and proximal regions[35]. However, BFlh architecture differs between regions, with shorter fascicles and larger pennation angle in the distal compared to the proximal region[35]. Thus, the distal region seems to be more suited to force production than the proximal region, which is more suited to larger excursions. On the contrary, Kellis et al.[36] found higher pennation angle in the proximal compared to the distal region in cadavers, which might be due to disagreement in BFlh pennation angles between cadaver and in vivo measurements[35]. Intervention studies are needed to examine associations between region-specific activity and architectural and morphological changes along the hamstrings.

Overall muscle activity

Since hamstring injuries are most common in BFlh, muscle-specific exercise selection based on the activity of individual hamstring muscles is of significant interest. Architecturally, longer fascicle length and lower pennation angle of ST compared to BFlh[28,37] suggests different functions of these muscles.

During NHE in the current study, ST showed higher relative activity compared to BFlh, which apparently associates with increased hypertrophy in ST relative to BFlh in response to NHE training[38]. On the contrary, in eccentric knee flexion[39] and NHE[18], ST and BFlh were equally activated based on bipolar EMG. However, mfMRI studies during eccentric knee flexion[13] and NHE[16] found higher activity in ST compared to BFlh, similar to the current study. The latter mfMRI study analysed 3 slices at 40, 50 and 60% muscle length. During

NHE in the current study, between-muscle differences were not as high as those found with mfMRI, but it is likely that this mfMRI study ignored the region of highest activity within BFlh, which is distal to 40% muscle length according to the current study.

In SDL, overall activity did not differ between muscles in this study. In a previous study, the mechanically similar Romanian deadlift was classified as an ST-dominant exercise based on bipolar EMG. On the contrary, another study[40] also using conventional bipolar EMG showed higher activity in BFlh than in ST during SDL. However, the same study compared these results to mfMRI data, and found that differences in T2 changes between muscles were not observed when 5 slices along the muscles were analysed, which is in accordance with the current study using HD-EMG. Although methods were not directly compared, on the basis of the above results it seems that HD-EMG can provide a more comprehensive estimate of overall muscle activity than conventional bipolar EMG configurations.

As noted, previous studies are not in agreement concerning the relative activity of ST and BFlh in hamstring exercises. To estimate whole-muscle activity with mfMRI, 3-5 slices have been analysed along hamstring muscles[15,38,40]. However, this approach is not directly comparable to EMG studies wherein data are usually collected from a small muscle region. Large differences in spatial resolution between these methods may be one reason for discrepancies between studies, although mfMRI and EMG also assess different physiological mechanisms; metabolic and neural activity, respectively. As a limitation, EMG is prone to cross-talk. In this study, EMG activity measured from the ST and BFlh could have been contaminated by the activity of the semimembranosus and the short head of the biceps femoris, respectively. This possibility was presumably minimised by several factors: careful electrode array location using ultrasonography; applying 10 mm inter-electrode distance[41] and using electrodes with a relatively shallow pick-up area; examining male athletes with relatively thin subcutaneous tissue over the hamstrings. We also tried to improve EMG normalisation by applying different MVIC tasks. However, studies targeting optimisation of EMG normalisation are needed to further improve comparability of muscles or muscle regions. Furthermore, deeper components of the hamstrings cannot be examined with surface EMG. HD-EMG may be a good complement to mfMRI to study ST and BFlh muscles, with real-time recording, financial considerations, and time-efficiency among the advantages of HD-EMG over mfMRI.

NHE and SDL for injury prevention

The issue of which exercises can help to prevent hamstring injuries is under debate. Regarding the mechanism of injury, most running-type injuries seem to happen in the late swing phase of high-speed running[42], whereas the hamstring muscle-tendon unit is actively lengthened and subjected to the highest forces and strain within the step cycle[43,44]. In this phase, hamstring muscles seem to be highly activated[45]. To mimic the injury mechanism, it is generally believed that eccentrically activating hamstring muscles at a longer muscle length would be optimal from an injury prevention perspective. Nonetheless, an increasing body of evidence suggests that the Nordic hamstring exercise, despite requiring a substantially shorter muscle operating length than in the late swing phase, has a preventive effect against hamstring injuries[7,9,46]. In NHE, ST was more active than BFlh, but both ST and BFlh were highly activated, supporting the idea of positive architectural changes (i.e. fascicle elongation) within BFlh in response to NHE intervention[38]. In SDL, hamstrings work at a longer muscle length than in NHE, and in this study relative activity of BFlh compared to ST was higher than in NHE (with negligible difference between muscles). However, absolute activity was substantially lower in both muscles (ST = 72% vs. 37%, BFlh = 64% vs. 36%, of MVIC on average in NHE vs. SDL). It should be noted that the load was not matched for the two exercises. Instead loads that are generally used in training were applied, making these exercises comparable from a practical point of view. Due to the relatively low activity level in the eccentric phase of SDL, we speculate that SDL alone may not be as effective as NHE to prevent hamstring injuries.

Within BFlh, we observed the lowest activity in the proximal region in NHE. This may be associated with higher strain close to the proximal muscle-tendon junction in BFlh during cyclic knee-flexion extension contractions[47]. Silder et al.[47] also observed higher strain in previously injured BFlh, which may be associated with lower EMG activity in the BFlh of the injured limb[48]. The association between strain magnitude and EMG activity level should be further studied to reveal whether HD-EMG may be a useful tool for hamstring injury risk management.

Compared to the knee-dominant NHE, based on mfMRI studies[14,24] we expected relatively higher activity in the proximal BFlh compared to the distal region in the hip-dominant SDL. Instead, similar proximal-distal activity patterns were observed in NHE and SDL. Even though the most proximal region cannot be measured with surface EMG, this study suggests that hip-dominant exercises do not necessarily activate proximal BFlh preferentially. Future studies should further examine whether the relative activity of muscle regions can be modulated with different exercises.

Perspective

Future studies should use HD-EMG to examine whether regional differences can be observed in other exercises and high-injury risk tasks. It should be emphasised that although proximal-distal differences seem to be significant, the clinical relevance of this phenomenon is yet to be clarified. In previously strained BFlh, decreased EMG activity[48,49], slower EMG onset[50] and decreased metabolic activity[15] were observed. It may be of value to examine whether inhibition is region-specific, and if exercise selection could affect the relative activity of muscle regions. This knowledge will help to identify the most suitable exercises for interventions and improve the restoration of neuromuscular function following a hamstring injury.

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TABLES, FIGURE LEGENDS AND FIGURES

Table 1. Differences (Cohen's *d* ±90% confidence limits) between the activity level of muscle regions for each muscle and exercise.

	Semitendinosus		**Biceps femoris long head**	
Region	middle	proximal	middle	proximal
		Nordic hamstring exercise		
distal	1.41 ±0.79^{L}	0.87 ±0.60^{L}	-0.87 ±0.38^{L}	-1.25 ±0.71^{L}
middle		-0.55 ±0.52^{M}		-0.38 ±0.53^{S}
		Stiff-leg deadlift		
distal	0.67 ±0.63^{M}	0.29 ±0.44^{S}	-0.16 ±0.27^{T}	-0.63 ±0.35^{M}
middle		-0.38 ±0.39^{S}		-0.48 ±0.29^{S}

T = trivial difference, S = small difference, M = moderate difference, L = large difference between regions. Positive and negative values refer to higher activity in the relatively more proximal and distal regions, respectively.

Figure 1. HD-EMG preparation.

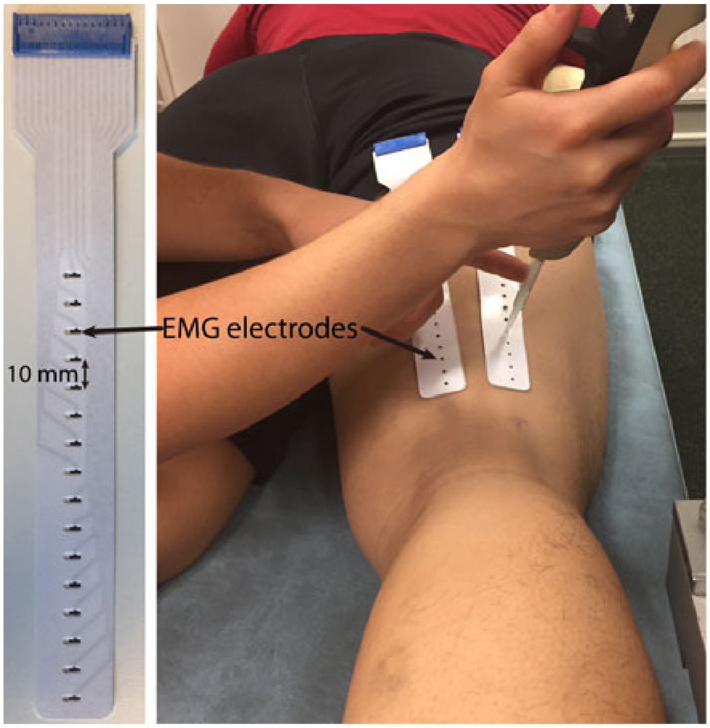

Figure 2. Distribution of normalised EMG signals in NHE.

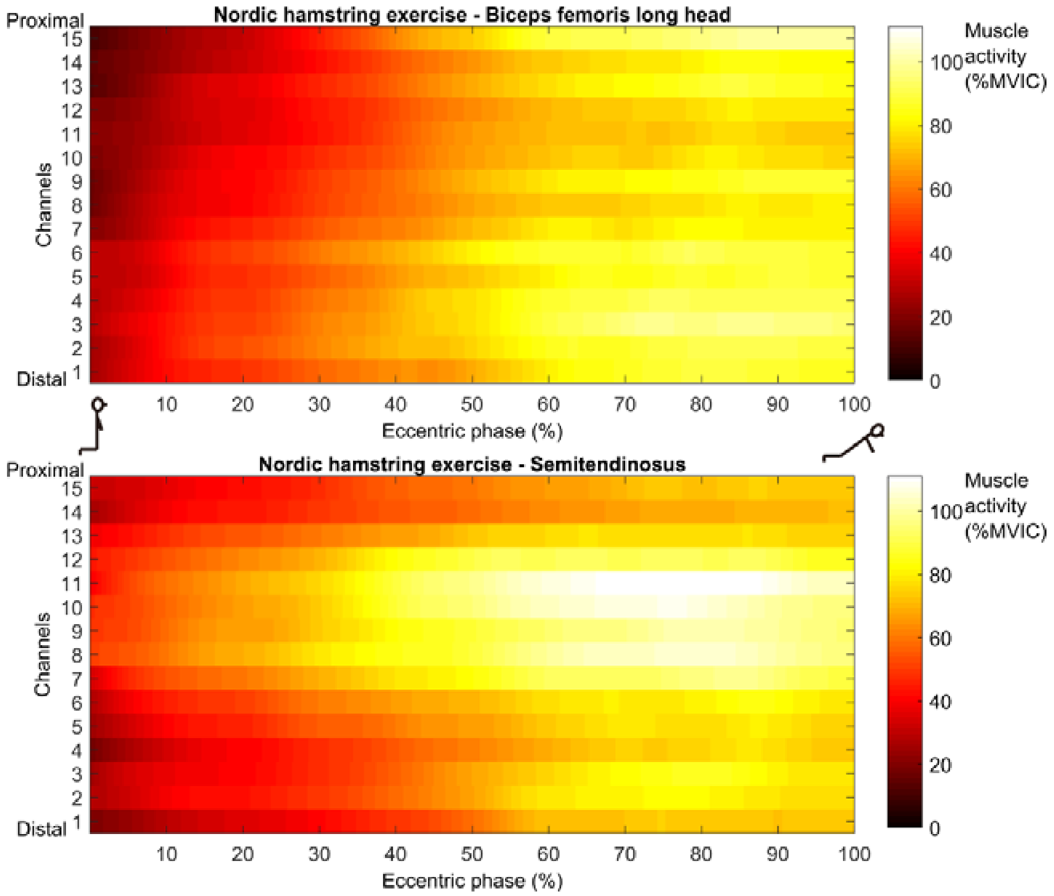

Figure 3. Distribution of normalised EMG signals in SDL.

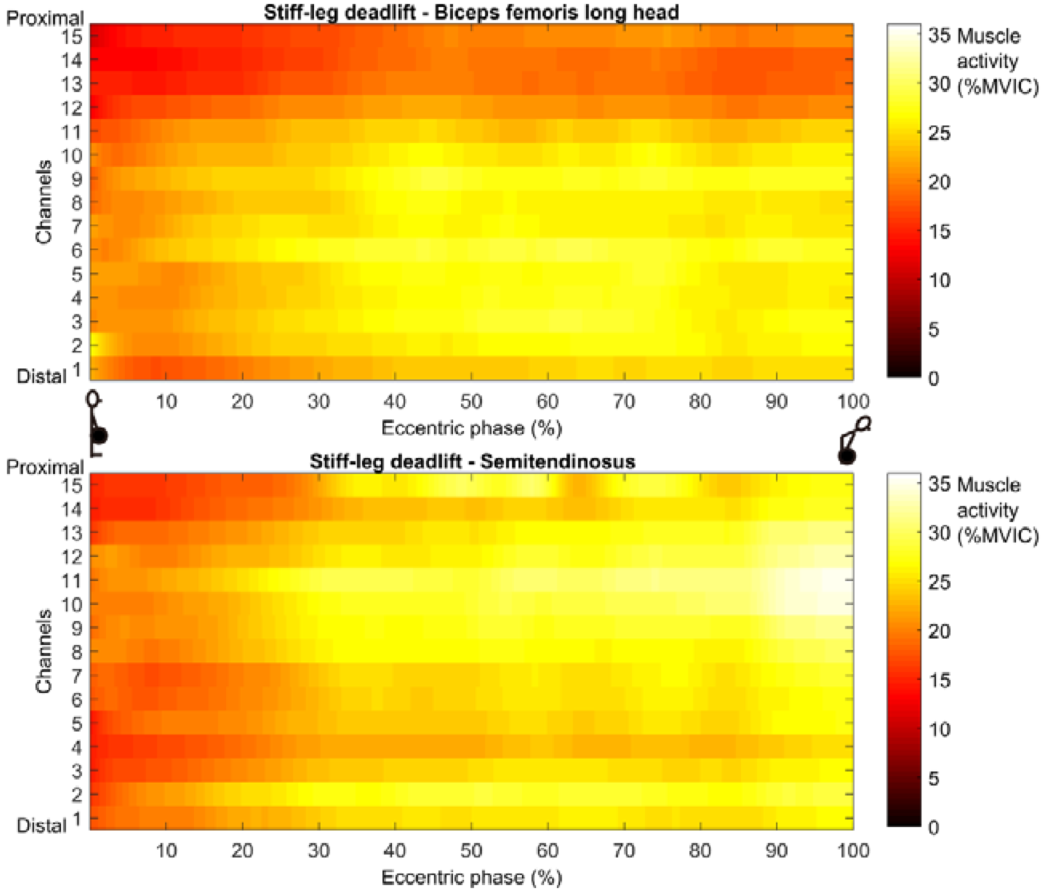

Figure 4. Regional activity for each participant.

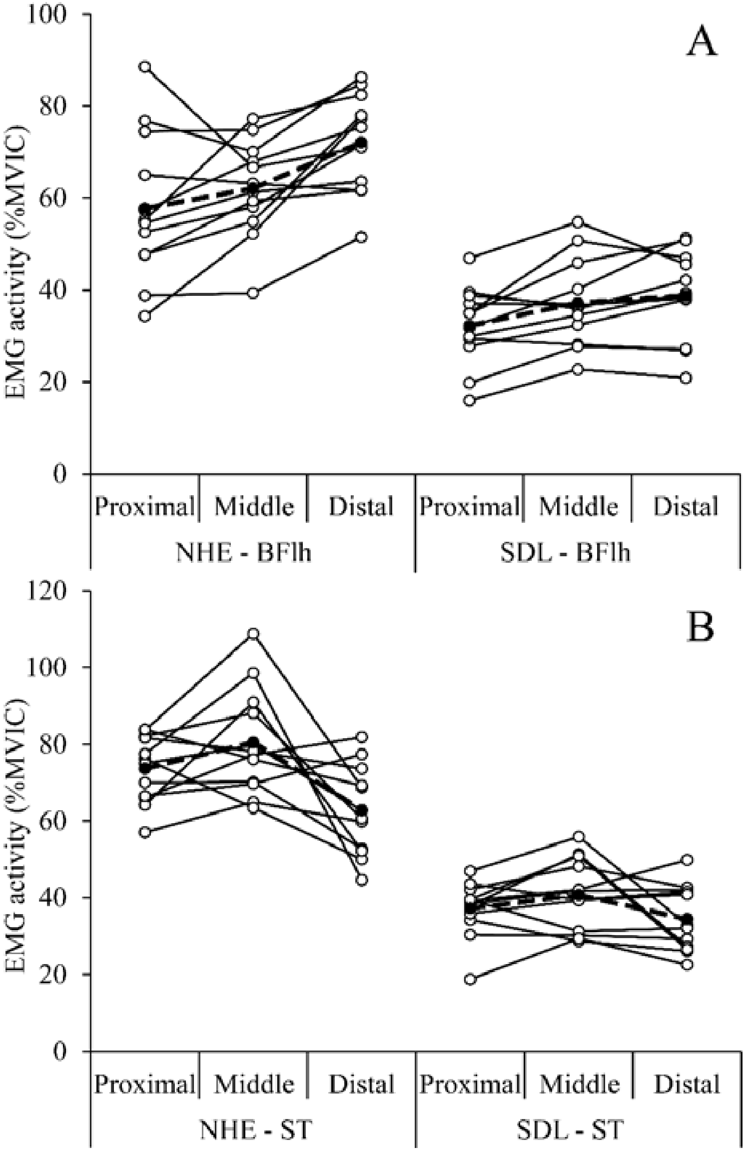

Figure legends

Figure 1. 15-channel high-density electromyography arrays were attached over the biceps femoris long head and semitendinosus to measure activity along the muscles. Electrode grids were filled with conductive gel for proper electrode-skin contact.

Figure 2. Normalised electromyographic (EMG) activity along the biceps femoris long head (upper panel) and semitendinosus (bottom panel) during Nordic hamstring exercise. The figure represents group average (N=12) for each channel of the EMG array along the corresponding muscle. EMG channels were time-normalised and low-pass filtered for visualisation. MVIC = maximal voluntary isometric contraction.

Figure 3. Normalised electromyographic (EMG) activity along the biceps femoris long head (upper panel) and semitendinosus (bottom panel) muscles during stiff-leg deadlift. The figure represents group average (N=12) for each channel of the EMG array along the corresponding muscle. EMG channels were time-normalised and low-pass filtered for visualisation. MVIC = maximal voluntary isometric contraction.

Figure 4. Regional electromyographic (EMG) activity as a percentage of the activity during maximal voluntary isometric contraction (%MVIC) in the biceps femoris long head (BFlh, panel A) and semitendinosus (ST, panel B) for each participant during Nordic hamstring exercise (NHE) and stiff-leg deadlift (SDL). Filled black markers connected with dashed lines represent group average.