IJSPT INTERNATIONAL JOURNAL OF SPORTS PHYSICAL THERAPY

Jorge A, Lichtenstein E, Faude O, Roth R. Muscle Activity and Kinematics During Three Hamstring Strengthening Exercises Compared to Sprinting: A Cross-Sectional Study. *IJSPT*. 2024;19(5):569-580. doi:10.26603/001c.116158

Original Research

Muscle Activity and Kinematics During Three Hamstring Strengthening Exercises Compared to Sprinting: A Cross-Sectional Study.

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Keywords: biceps femoris, electromyography, exercise, hamstring injury prevention, high-speed running, joint-dominance, semitendinosus

https://doi.org/10.26603/001c.116158

International Journal of Sports Physical Therapy

Vol. 19, Issue 5, 2024

Background

During sprinting, the biceps femoris long head predominantly gets injured, while hamstring strengthening exercises predominantly activate the semitendinosus more effectively. Understanding how joint dominance influences hamstring activity may offer clarity on appropriate exercise selection in strengthening programs.

Purpose

This study compared three hip-dominant hamstring exercises: the rocker, perpetuum mobile fast and slow (PMfast and PMslow) and the Nordic Hamstring exercise (NHE) on their potential to simulate sprint-like activity and kinematics.

Methods

Muscle activity of the posterior kinetic chain (biceps femoris, semitendinosus, gluteus maximus, and medial gastrocnemius) was measured with surface electromyography (sEMG) during the exercises and treadmill running at 75% of the individual maximal sprint velocity in male athletes. sEMG data were normalized to maximal sprinting. 3D-motion capture was employed to assess hip and knee angles.

Results

Eight male athletes were included (age: 24.0 years ± SD 2.9; body mass: 76.8 kg ± 7.7; height: 1.79 m ± 0.08). Greater activity of the hamstrings occurred during the explosive exercises ranging from 63.9% [95%CI: 56.3-71.5%] (rocker) to 49.0% [95%CI: 40.4-57.6%] (PMfast) vs. 34.0% [95%CI: 29.1-38.9%] (NHE) to 32.1% [95%CI: 26.9-37.3%] (PMslow). The rocker showed greatest hamstring and gluteus maximus activity. Biceps femoris consistently showed greater activity than the semitendinosus across all exercises in peak (mean difference: 0.16, [95%CI: 0.07-0.26]) and average (mean difference: 0.06, [95%CI: 0.01-0.11]) activity. PMfast, PMslow and NHE demonstrated less hip flexion angle at peak hamstring activity than the rocker and high-speed running and every exercise showed less hamstring elongation stress than during high-speed running.

Discussion

Hamstring activity is comparable to high-intensity treadmill running for NHE and PMslow, and greater for the rocker and PMfast. Gluteus maximus activity varied, with the

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rocker and PMfast showing greater activity than in sprinting. All examined exercises demonstrated their peak activity at short hamstring muscle length.

Level of evidence

3b

INTRODUCTION

Sprinting is a key activity and a determinant of performance in many sports such as soccer, rugby or track and field. However, sprinting near maximum velocity is the main activity during which hamstring muscle injuries typically occur.[1-3] Muscle injuries are frequent throughout many sports,[4-7] with a high risk of recurrence and creating above average time-loss from competition.[4,6,8]

The bi-articular hamstrings are subjected to a stretch-shortening cycle during sprinting, with stretching taking place in the terminal swing phase and shortening starting shortly before the foot strike and lasting throughout the stance phase.[2] This coincides with neuromuscular activation being most pronounced within those time frames.[9] From a kinematic standpoint, the bi-articular hamstrings reach their greatest muscle-tendon length during the terminal swing phase.[2] The majority of data suggests that injuries typically occur during terminal swing phase, though it is still a matter of debate.[10] This phase is characterized by peak muscle-tendon force, high muscle excitation, negative work, and peak muscle-tendon length.[2,9,11,12] Out of all hamstring muscle injuries, approximately 70% affect the biceps femoris long head (BFlh) with lesions evenly distributed throughout the muscle.[13] The exposure to a greater lengthening strain of the BFlh may be explained by the relatively longer hip extension moment arm,[14] its lower stretch tolerance or its ability to store energy through negative work compared to the other hamstring muscles.[15]

It might be appropriate to consider these factors when selecting isolated training exercises to properly address the specific hamstring activation during late swing in combination with the prevailing lengthening stress. Therefore, it may be reasonable to assess exercises for their capacity to simulate sprint-like conditions.

The Nordic hamstring exercise (NHE) has demonstrated its effectiveness regarding reducing the risk of hamstring injuries. Several meta-analyses have shown that programs consisting of or including the NHE revealed a remarkable decrease in hamstring injury incidence of about 50%.[16-18] In several cross-sectional studies assessing muscle activity, the NHE demonstrated the greatest eccentric muscle activity out of a variety of exercises.[19-21] Nevertheless, hamstring injury incidence is still rising in professional football.[6] It has been speculated that hamstring exercises including the NHE lack sprint-specificity.[19,22-24] Therefore, such exercises may not fully realize the potential transfer of strength gains into horizontal force production or capabilities to resist muscle strain stress.[24] In addition, numerous studies indicate that hamstring exercises, including the NHE, typically result in a more pronounced activation of the semitendinosus muscle (ST).[19,25-27] Both aspects may limit the efficacy of injury prevention exercises. Studies using functional magnetic resonance imaging suggest that hip-dominant exercises (hamstring activation through hip extension) may lead to a greater activity of the BFlh.[28] Hence, this study aimed to investigate two hip-dominant hamstring exercises, which may more closely reflect the electromyographical activity and kinematic characteristics of sprint / high-speed running. Together with the NHE, these exercises were compared through application of sprint normalization.[29]

This study aimed to analyze the peak and average muscle activity as well as joint angles of peak activity and resulting elongation stress (subtraction of knee from hip angle) of the posterior kinetic chain during several exercises and high-speed running. The purpose of this study was to compare three hip-dominant hamstring exercises: the rocker, perpetuum mobile fast and slow (PM_{fast} and PM_{slow}) and the Nordic Hamstring exercise (NHE) on their potential to simulate sprint-like activity and kinematics. It was hypothesized that (1) BFlh excitation would be greater in hip-dominant exercises than in the knee-dominant exercise, (2) BFlh-ST ratio would differ depending on dominant joint, (3) elongation stress during exercises would be significantly smaller than in treadmill high-speed running.

MATERIAL AND METHODS

STUDY DESIGN AND PROCEDURE

The cross-sectional intervention study was conducted with adult male athletes from sprint intensive sports. Participants performed two maximal and one submaximal sprints and four selected exercises in one testing measurement session. Muscular activity of the biceps femoris and semitendinosus as well as hip and knee joint angles were assessed. The study protocol complied with the latest version of the Declaration of Helsinki and was evaluated and approved by the regional ethics committee.

PARTICIPANTS

This study recruited amateur athletes from surrounding clubs via convenience sampling from December 2022 to September 2023. Inclusion criteria were male sex, between 18 and 30 years old, with at least one year of more than 4.5 hours of sprint-related training per week to ensure that both performance and technical proficiency would be homogeneous in sprinting. Athletes with recent injuries in lower extremities in the prior six months as well as the presence of any kind of discomfort or pain during sprinting were excluded from participation. Participants were informed about the study and all procedures and signed a written consent before participation.

EXPERIMENTAL PROTOCOL

Athletes were scheduled for two sessions. The first habituation session, served to familiarize the standardized warm-up, ensure correct technical execution of the exercises and to determine exercise load. This session lasted approximately 45 minutes and took place at least 48h prior to the second session. The second testing session consisted of a warm-up, two maximal sprints, a submaximal high-speed run at 75% of maximal sprint and the four exercises in randomized order. This session lasted about two hours.

At the beginning of the testing session, standardized surface electromyographic sensors (sEMG) were applied to four muscles of interest (biceps femoris long head [BF], semitendinosus [ST], gastrocnemius medialis [GCM], gluteus maximus [GMax]) on the right leg of each participant. Sensor application was in accordance with the SENIAM guidelines (http://www.seniam.org). Before electrode fixation, the skin was shaved, abraded with scrubbing gel and wiped with alcohol. Electrodes were placed parallel to the muscle fibers with an inter-electrode distance of 20mm. After a resting period of 5 min, impedance was tested (<10kΩ) and correct electrode placement was verified through manual muscle test and visual inspection of raw signals. The standardized 20 min warm-up consisted of running drills, mobilization exercises and time for individual necessities designed to enable maximal sprinting. After warming up two 40 m maximal sprints on an outdoor sprint track with similar weather conditions for all participants (dry, sunny, about 25°C) and a resting period of 5 min in between were performed. Participants started from a standing start with self-chosen set-off with their usual running shoes performing with maximal effort. Velocity calculations based on 35 to 40m sprint time was obtained through a single-beamed photocell (Witty, Microgate Srl, Bolzano, Italy).

After a 10-minute rest, three-dimensional (3D) motion capture system (Vicon Motion Systems Ltd, United Kingdom) reflective markers were bilaterally placed on the lower body with a total of 36 markers positioned on anatomical landmarks. After calibration of the motion capture model, participants performed one high-speed run at 75% of maximum sprint velocity on a motorized treadmill. It has been shown that this is the fastest speed which does not lead to technical failure within 15 strides and still represents kinematics close to a maximal sprint.[30] Subsequently the four exercises of interest were conducted. Three repetitions were completed per exercise, with a 5 min rest in between, and the order was randomized as to avoid the influence of fatigue or order bias. Constant speed, pelvic tilt and leg alignment were controlled to ensure similar interindividual movement execution. Perceived loading and exertion were quantified with the Borg CR10 scale[31] immediately after exercises and before initiating the new one to ensure that the participants were sufficiently recovered.

EXERCISE DESCRIPTION

The rocker is a custom-made apparatus which is currently used by Swiss track and field athletes on national level (Figure 1A). The hip is secured to the device, the right leg elevated on a 42 cm high surface padded with a mat (Balance-pad Elite, Airex AG, Sins, CH). The device weight additional to the body weight gets lifted through unilateral hip extension. Participants were instructed to thrust their hip as high and explosively as possible. The rocker operates as a class 2 lever system and has multiple resistance levels, with increasing intensity moving the fulcrum further cranially. This level was individually adjusted during habituation for highest possible load with no significant decrease in execution speed for three repetitions without technical failure.

The perpetuum mobile exercise (Figure 1B) originates from physical therapy and is used to train reactive hip stabilization and propulsion in gait as described by Klein-Vogelbach.[32] Participants positioned their shank atop a gymnastic ball (53cm diameter), while hip and left leg stayed airborne, supported through the arms spread on the ground. In the starting position the ball was fully pulled towards the hip. Through extension in the hip the ball was rolled caudally while the left leg imitates the swing during running cycle through hip and knee flexion. The exercise was performed in two variations: one with an explosive concentric phase (PM_{fast}) and the other with every movement phase lasting five seconds controlled with a metronome (PM_{slow}).

A custom-made device with adjustable slope was used to perform the NHE (Figure 1C). Participants knelt on a padded board, with the ankles secured directly superior to the lateral malleolus by individual ankle braces. Only the lowering (eccentric) portion of the exercise was performed. Starting from an initial kneeling position with arms on the chest, participants were instructed to lower their bodies while keeping an extended hip, reaching ground contact after five seconds. During habituation session, the slope level was adjusted to ensure that the shank angle allowed for exactly three technically correct full range of motion repetitions without loss of control.

DATA COLLECTION AND ANALYSIS

Muscular activity was measured through bipolar surface electrodes (Wave Plus, Cometa srl, Milan, IT) with an interelectrode distance of 20mm, at a sampling rate of 1 kHz. Raw EMG data were filtered using the Butterworth bandpass filter (10-400Hz), full-wave rectification, and smoothed by a root mean square (25ms width) using the proEMG software (prophysics AG, Kolten, CH). Peak and average (contraction phase) RMS values of every repetition of every exercise were extracted and the median activity for every exercise was calculated. sEMG data were normalized based on maximal sprint, utilizing the greater activity out of the two tries. The 30ms plateaus were averaged over three consecutive strides and applied for every muscle of interest.[29] BFlh/ST-ratio was calculated by dividing BFlh activity by ST activity.

The 3D motion capture utilized twelve cameras with a recording frequency of 200 Hz. The musculoskeletal model based on Vicon Plug-In Gait Lower Body AI was modified by additional markers (Figure 2) to best facilitate the modelling of the submaximal sprints and exercises according to prior tests.[33] Raw trajectory data was processed using

Figure 1. Start and end position of every exercise.

From top to bottom: (A) the rocker, (B) perpetuum mobile, and (C) the Nordic Hamstring. Note: Perpetuum mobile consists of two execution variations (fast and slow).

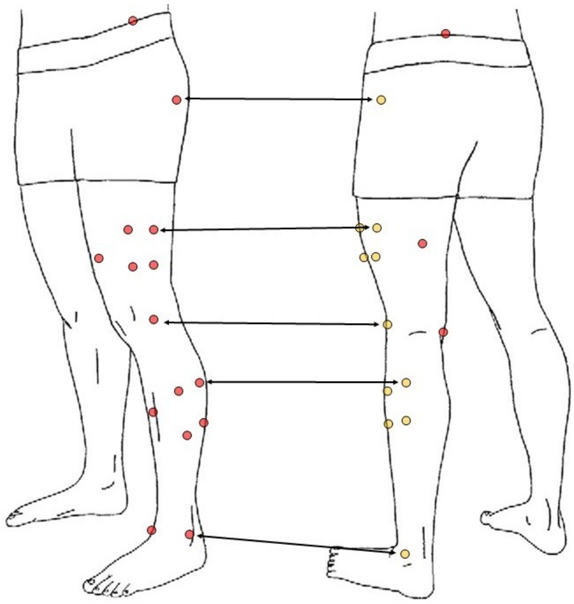

Figure 2. Illustration of the 18 reflective markers used per limb. The markers that appear twice are highlighted in orange in the second frame.

software inbuilt pipelines for dynamic movements (Vicon Nexus 2.15, Vicon Motion Systems Ltd, United Kingdom). 3D motion capture data was synchronized with the EMG data. Hip and knee joint angles corresponding to the maximal muscle activity in the BF and ST were recorded and the median of the three repetitions per exercise was used for further analysis. Joint angles were measured as depicted in Figure 4A. Elongation stress was calculated by subtracting knee flexion angle from hip flexion angle.[22]

STATISTICAL METHODS

A random effects linear mixed model (GAMLj, Jamovi) was employed to examine differences in muscular activity (peak and average) for each muscle and angles in hip and knee, elongation stress and BFlh/ST-ratio in hamstrings. Random intercept per participant model was used to account for repeated measures. All values are reported with mean difference (MD) and confidence interval (CI), and level of significance was set at $p < 0.05$. Standardized effect sizes (SMD) were acquired by standardizing all estimates to the treadmill SD. Normal distribution of residuals was verified visually through inspection of Q-Q-Plots.

RESULTS

Descriptive data is shown in Table 1. Post-hoc computation of achieved power showed us values > 0.92 for the applied statistical calculations.

MUSCULAR ACTIVITY

Peak and average EMG data for hamstrings is visible in Table 2. The rocker showed significantly greater peak hamstring activity than PM_{slow}, NHE and high-speed running (MD: 0.28-0.39, p< 0.006, [95%CI: 0.13-0.54], SMD: 1.5-2.0). Average hamstring activity in the rocker was significantly greater than in any other exercise (MD: 0.15-0.35, p< 0.002, [95%CI: 0.08-0.42], SMD: 1.9-4.4). Additionally, in PM_{fast} hamstring activity was significantly greater than in PM_{slow}, NHE and high-speed running (MD: 0.15-0.20, p< 0.002, [95%CI: 0.07-0.27], SMD: 1.9-2.5). BFlh activation was consistently greater in peak (MD: 0.16, p< 0.002, [95%CI: 0.07-0.26], SMD: 0.8) and average activity (MD: 0.06, p< 0.014, [95%CI: 0.01-0.11], SMD: 0.8) compared to the ST.

Peak and average muscle activity of all muscles is depicted in Figure 3. Peak GMax activity was significantly greater in the rocker, $PM_{fast,}$ and high-speed running than in NHE (MD: 1.08-1.43, p< 0.004, [95%CI: 0.55-1.94], SMD: 1.7-2.3), as well as to a smaller extent in the rocker than in PM_{slow} (MD: 0.85, p= 0.047, [95%CI: 0.30-1.39], SMD = 1.3). Average GMax activity in the rocker and PM_{fast} was significantly greater than in PM_{slow} and NHE (MD: 0.37-0.68, p< 0.038, [95%CI: 0.13-0.89], SMD: 1.6-3.0). GCM activities of every exercise showed significantly smaller values than during high-speed running for peak (MD: 0.37-0.74, p< 0.009, [95%CI: 0.18-0.94], SMD: 1.0-2.0) and average activity (MD: 0.18-0.28, p< 0.001, [95%CI: 0.11-0.36], SMD: 1.2-1.8), respectively.

Table 1. Demographics of all male participants

	Mean ± SD
n	8
Height [m]	1.79 ± 0.08
Body mass [kg]	76.3 ± 7.7
Age [yr.]	24.0 ± 2.9
Training Age [yr.]	9.0 ± 3.8
Training hours per week [h]	5.0 ±1.8
Sprint Time [s]	5.24±0.32
max. Verlocity [km/h]*	31.9 ± 2.5
75%max Sprint	23.9 ± 1.87

*Maximal sprint velocity was calculated based on the sprint time between 35 and 40m.

Table 2. Peak (PV) and average (AV) sprint normalized EMG group mean data for the four exercises and high-speed running divided by lateral and medial hamstring.

	Mean [95%CI]			
Exercise	Sprint PV		Sprint AV	
	BFlh	ST	BFlh	ST
Rocker	1.32 (1.05-1.59)*	1.04 (0.90-1.17)	0.70 (0.56-0.84)	0.58 (0.51-0.65)
PM_{fast}	1.11 (0.91-1.32)	0.90 (0.72-1.07)	0.54 (0.39-0.68)	0.44 (0.32-0.57)
PM_{slow}	0.89 (0.69-1.09)	0.80 (0.58-1.01)	0.35 (0.25-0.44)	0.30 (0.22-0.37)
NHE	0.99 (0.72-1.26)	0.79 (0.65-0.94)*	0.36 (0.26-0.45)	0.32 (0.26-0.39)
Treadmill	0.80 (0.65-0.95)*	0.78 (0.59-0.96)*	0.30 (0.23-0.37)	0.28 (0.22-0.35)

* different peak activity from activation during maximal sprint (1)*PM_{fast}*: perpetuum mobile exercise fast version; *PM_{slow}*: perpetuum mobile exercise slow version; *NHE*: nordic hamstring exercise

HIP AND KNEE FLEXION ANGLE

Angles of peak activity as well as elongation stress are shown in Table 3. Hip flexion angle differed significantly between exercises. High-speed running (MD: 34-38°, p< 0.001, [95%CI: 21-51°], SMD: 2.6-2.9) as well as the rocker (MD: 19-23°, p< 0.044, [95%CI: 7-36°], SMD: 1.5-1.8) displayed a more flexed hip than the other exercises (Figure 4). No differences in knee flexion angle were observed (MD: 1-20°, [95%CI: -9-34]) except a significantly more flexed knee during the rocker than during PM_{slow} (MD: 27°, p= 0.013, [95%CI: 11-42°], SMD: 1.4). Elongation stress of peak hamstring activity was smaller for every exercise than for high-speed running (MD: 25-29, p< 0.001, [95%CI: 16-37], SMD: 2.1-2.5).

MUSCLE SELECTIVITY

Muscle selectivity of every exercise is shown in Figure 5. Peak and average activity BFlh/ST-ratio did not differ between exercises (MD = 0.02-0.35, [95%CI: -0.23-0.41]).

DISCUSSION

The hamstrings are frequently prone to injury. Gaining insight into how various exercises activate the individual muscles and considering the influence of joint dominance could provide clarity on the appropriate exercise selection in strengthening programs. This study evaluated muscle sprint-specificity of three hip dominant exercises looking at task-specific muscle activity and joint angles. The main findings were that the rocker elicited greatest muscle activity in BFlh and ST followed by PM_{fast}. NHE showed high peak, but low average normalized muscle activity (Table 2). All examined exercises demonstrated their peak activity at short hamstring muscle length (range) with none of them reaching elongation stress of 0. This represents the average elongation stress at peak activity determined during at least 10 running cycles on the treadmill.

MUSCLE ACTIVITY

The results consistently demonstrated high peak normalized muscle activity for all exercises in reference to the utilized thresholds by other sEMG studies that consider high muscle excitation over 60 to 80% of MVIC normalized activity.[19,23-25,34] The contraction phase averages of this study are barely smaller than the peak sprint normalized activity in the reference studies.[19,23,24] Therefore, rather than evaluating the results based on absolute values, as is common in EMG studies for activity assessments, the data were examined in relation to each other and referenced to the sprint. The results show that the explosive exercises elicit

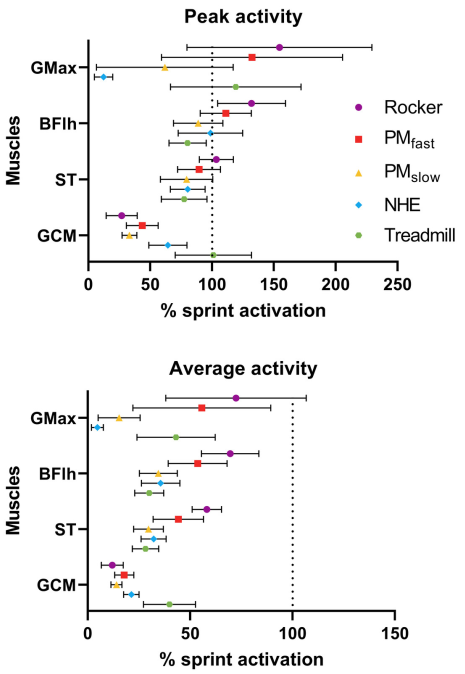

Figure 3. Sprint normalized peak (1A) und average (1B) activity (95% CI) of the posterior kinetic chain of all examined exercises and treadmill high-speed running. The dotted line corresponds to the peak muscle activation for each muscle during sprinting.

Note: 100% lines are in different scales. PM_{fast}: perpetuum mobile exercise fast version; PM_{slow}: perpetuum mobile exercise slow version; *NHE*: nordic hamstring exercise. *GMax*: gluteus maximus; *BFlh*: biceps femoris long head; *ST*: semitendinosus; *GCM*: gastrocnemius medius.

greater average hamstring muscle activity in comparison to the slow exercises which induced between 26-40% of maximal sprint for NHE and 25-39% for PM_{slow}. There are several possible reasons. Firstly, one can assume that a contributing factor is the extra load imposed by the rocker on hip extension. As demonstrated in previous research,[35] increased load enhances muscle activity, which could offer a partial explanation for the observed greater muscle activity. Secondly, overall peak normalized EMG showed more similar values among exercises, in contrast the discrepancies are great in average normalized values (Figure 3). The reason may be the explosive exercises having short concentric phases where average activity approximates peak activity while slow exercises have longer contraction windows that allowed for more fluctuations and therefore smaller average values. In addition, during initial phase of the NHE the load is negligibly small which also pulls down the average EMG values. Lastly, variations in execution may influence muscle activity magnitude during the NHE. Previous research has incorporated variations with a more flexed hip and different shank angles.[36] All variations exerted less activity in hamstring muscles than the original with neutral hip and shank level which is in accordance with another similar study.[37] It seems that similarity to sprinting in NHE faces a trade-off in less activity magnitude. Since the previously reported study showed NHE hip flexion angles closer to sprint conditions and more extended knee starting angle,[36] this could also be the case for the procedure of this study. This would imply that EMG values during NHE could reach higher levels with a different execution, making its execution comparable to the rocker.

To the authors knowledge there are only few explosive hamstring exercises examined in a closed kinetic chain as seen in the rocker and PM_{fast}. Two studies examined the laying kick,[21,23] a related movement involving a unilateral glut bridge with 90° knee flexion angle in the hip extending extremity with the contralateral side kicking up explosively as to lose ground contract with the supporting leg. Although no additional load was used both studies reported among the greatest hamstrings and GMax excitation. Both study outcomes support the finding of this study advocating for closed kinetic chain hip-dominant exercises.

Hip-dominant exercises, especially like the rocker and PM_{fast} revealed high variability of GMax activity, these high deviations are also visible in the previously reported study.[21] It seems unlikely that this spread originates from the generated maximum values while sprinting because with increasing speed leg muscle activation patterns get more repeatable.[38] Ultimately, this consolidation results in a "motor program getting dominant" during maximal sprinting leading to utilization of a uniform neural strategies.[39] A more probable reason lies in the exercises being new to most participants leading to them using different neural strategies. Therefore, explosive hip extension may be achieved with or without much participation of GMax.

Table 3. Mean hip and knee flexion angles of peak EMG activity averaged for both hamstrings in degrees and resulting elongation stress at which peak activity occurs.

	Mean [95%CI]		
Exercise	**Hip flexion angle**	**Knee flexion angle**	**Elongation stress**
Rocker	44 (35 ; 52)*	69 (59 ; 79)†	-25 (-35 ; -16)
PM_{fast}	24 (8 ; 40)	49 (34 ; 65)	-25 (-29 ; -22)
PM_{slow}	20 (4 ; 37)	42 (23 ; 61)†	-22 (-26 ; -18)
NHE	24 (20 ; 29)	50 (39 ; 61)	-26 (-34 ; -18)
Treadmill	58 (52 ; 65)***	56 (45 ; 66)	3 (-3 ; 9)***

PM_{fast}: perpetuum mobile exercise fast version; PM_{slow}: perpetuum mobile exercise slow version; *NHE*: Nordic hamstring exercise.
* different from the rest (<0.05)
† different from each other (<0.05)

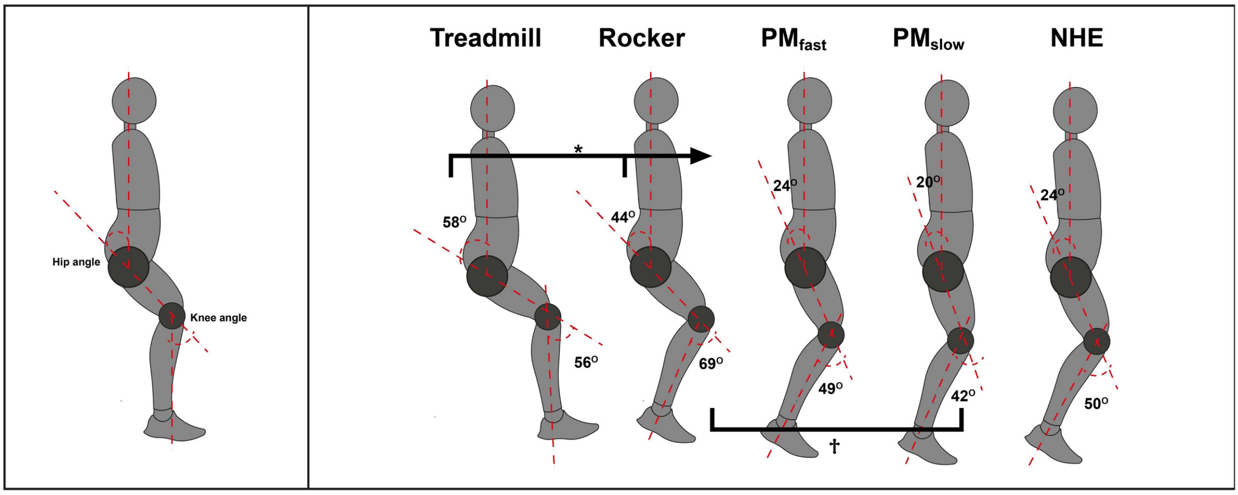

Figure 4. Definition of joint angles (A) and hip and knee flexion angles of peak muscle activity during every exercise and high-speed running (B) averaged for both hamstrings.

PM_{fast}: perpetuum mobile exercise fast version; *PM_{slow}*: perpetuum mobile exercise slow version; *NHE*: Nordic hamstring exercise.
* different from the rest to the right (<0.05)
† different from each other (<0.05)

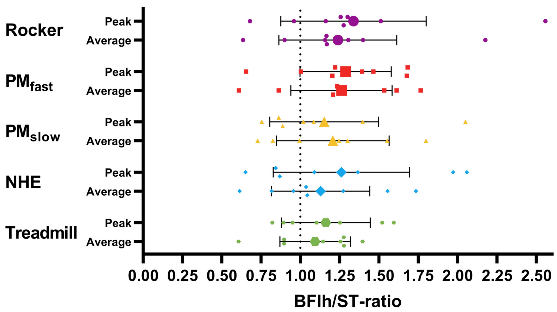

Figure 5. Peak and average sprint normalized ratio of BFlh and ST activity (95%CI) for every exercise and treadmill high-speed running with the dotted line symbolizing equal intermuscular activation.

PM_{fast}: perpetuum mobile exercise fast version; *PM_{slow}*: perpetuum mobile exercise slow version; *NHE*: Nordic hamstring exercise.

Further research is needed to determine if this variability decreases with experience ultimately answering the question of hamstring selectivity of the examined exercises.

In the present study, treadmill high-speed running elicited among the lowest level of peak and average hamstring muscle activity. This contrasts the results of another study which also investigated 75% of maximal sprint (24.4 km/h ± 1.4km/h) and found that chosen speed already elicited greater BF and ST activity than maximally executed exercises.[30] Despite employing similar speeds (23.9 km/h ± 1.9 km/h), the present study did not reach the same conclusion. One plausible explanation for this phenomenon could be the running velocity-dependent engagement of the hamstring muscles. During higher velocities, specifically at speeds exceeding 26 km/h, a 30% increase in running speed results in approximately a doubling of the demands on the hamstring muscles.[40] This sensitivity to speed fluctuations might account for the difference in EMG levels present. Hence, it may be that used running speeds are not as representative of maximal sprint kinematics as initially anticipated.

HIP AND KNEE FLEXION ANGLES

Angles of peak activity for high-speed running at 75% of maximal speed was at approximately the same time in late swing for both hamstring muscles and is consistent with findings of previous studies.[23,41] NHE presented a peak activity hip flexion angle of 26° (CI: 18.8°;33.3°) which occurred at 68.1% (CI: 61.5%;74.6%) of movement progression and was also visible in a similar study,[23] which showed an even greater hip flexion. This is noteworthy as participants were instructed to perform the exercise with the effort to keep the hip fully extended and was strictly controlled by the instructor when hip flexion was visible. As anterior pelvic tilt shifts optimal hamstring muscle length during movement progression, this can affect angle of peak activity as it prolongs hamstring optimal force generation. Thus, potentially, the window in which peak activity could occur may increase. Hip and knee flexion angles for PM_{fast} as well as for the NHE show similar composition as during high-speed running. The similarity entails that they exert peak hamstring activity at a similar time as during the late swing phase even though contraction modes in joints differ. The rocker displayed the most flexed hip next to high-speed running which indicates that peak hamstring activity occurs during the initial phase of the movement. On the other hand, if the knee was too flexed, it could target and adapt hamstring muscles at an unfavorable angle in the knee. This issue may be resolved by adjusting knee starting angle to be more extended. Shifting peak activity to a later stage of movement could potentially enhance hamstring engagement.

Elongation stress is a measure to quantify lengthening stress on the hamstrings by subtracting the knee from the hip flexion angle.[22] For reference, elongation stress during the late swing phase corresponds to a maximum value of 32 (i.e. 60° hip flexion -28° knee flexion) and starting position in NHE equals to -90 (0° hip flexion – 90° knee flexion). As hypothesized, none of the exercises came close to elongation stress values during high-speed running. Elongation stress, as a simple measure, neglects the greater moment arm at the hip. Given that all exercises exhibited less hip flexion than during treadmill high-speed running (Table 3), the actual elongation stress and therefore muscle length at peak activity would likely be less.[22] It is recommended to use exercises for hamstring muscle injury (HMI) prevention that stretch the hamstrings over their optimal length (>0), to induce changes in fascicle length effectively moving knee flexor torque-joint relationship to a more extended knee. At least from this point of view, the selected exercises including the NHE are not suitable for reducing the risk of HMI. On the contrary, concentric exercises can even lead to shortening of the muscle fibers.[42] Elongation stress for high-speed running was surprisingly low considering that peak activity coincides with peak lengthening stress on the hamstrings.[41] Though these values correspond to the results of another similar study.[23] This implies that between 75% and maximal sprint speed elongation stress increase by a collective amount of 30 angle units. Thus, the kinematics at this speed do not stress the hamstrings to a comparable extent as in maximal sprint, as originally assumed.

MUSCLE SELECTIVITY

As hypothesized, two of the three hip-dominant exercises elicited greater BFlh activity than the NHE but BFlh/ST-ratios did not differ depending on joint-dominance. Regarding this, a study examined the "stiff-leg deadlift" and found significantly greater BFlh and SM activity than in ST. They argue that ST's selectivity for eccentric knee-flexion may be attributed to its morphological properties, including long fibers with many sarcomeres in series, allowing it to contract over large distances. In contrast, BFlh and SM, as pennate muscles with a substantial cross-sectional area, are essential for high torque production. They conclude that medial and lateral hamstrings each have one muscle primarily responsible for high-excursion movements predominantly through the knee joint and one muscle for high-torque particularly in the hip joint.[43] Their suggestion is substantiated by a review of this possiblity.[28] This partially accounts for the greater activity of the BFlh in hip-dominant exercises but it does not apply to the NHE which is proven many times to be a ST-favoring exercise,[23,24,27,36,44] although there are studies that did not find significant activity differences between BFlh and ST.[19,21] A study which examined NHE and "stiff-leg deadlift" reported greater BFlh than ST activity for NHE which supports the presented results.[45] However, the muscle of greatest activity greatly varied between individuals. This is consistent with another study whose results indicate that hamstring activity cannot be solely based on joint dominance.[46] The BFlh/ST activity ratio of the latter also showed large individual variability, suggesting individual neural strategies for the activation of these muscles in running and sprinting as well as exercises. Great interindividual variability in muscle activity-dominance was the case for this study's results but does not add to the explanation of why mean ratios were all in favor of BFlh.

ST is selectively more active when a high shortening capacity and speed is required (preferably in combination). BFlh seems to have a certain affinity with hip movements, also due to the longer lever arm.[14,28] The selected exercises in the current study all utilize small ranges of motion at short muscle length with the rocker additionally demanding high torque levels. This could account for the consistent observation of BFlh/ST ratios exceeding 1 in the examined hip-dominant exercises. However, the limited range of motion alone does not provide a sufficient explanation for this ratio in the context of the NHE. Next to the possibility of BFsh crosstalk, execution type of NHE can be a possible reason as it alters the activity magnitude and pattern.[36] In the present procedure, shank level was adjusted for the exercise to be technically correct for three repetitions, ensuring no signs of early loss of control. Consequently, NHE starting position was at an average knee flexion angle of 81.5° (CI: 65.1°;98.0°). This reduction in range and absence of a breakpoint may alter the contribution ratio over one and may be further supported by two studies who found that ST activity is greater during the initial movement and relative BFlh activity progressively increases towards full knee extension.[37,47] This study's findings of NHE execution variation add evidence to the already stated suggestion that full ROM without loss of control could improve BFlh selectivity in NHE.

METHODOLOGICAL LIMITATIONS

It should be noted that the use of single surface EMG gives an estimate of only one area of the muscle and is prone to crosstalk.[48] Additionally, muscle activity does not always correlate to peak muscle forces, requiring the need to make assumptions in the absence of peak muscle force data. Lastly to control load as an effect modifier, the authors decided to adjust the intensity of those exercise where it was possible. In doing so, load became a potential source of error because the effort to standardize load may have altered the kinetics of the rocker and the NHE between subjects which in turn potentially increased variability of angle values and possibly muscle activation.

PRACTICAL APPLICATIONS

The outcomes of this study are intended to provide insights for practitioners, therapists, and researchers exploring sprint-specific alternatives to the NHE. The authors found alternatives that elicit the same or greater activity in hamstrings and can be used in different training states reaching as far back as early therapy stages. Based on the findings, it seems advisable when utilizing the NHE to do so in its full ROM to improve BFlh selectivity and to combine hip- and knee-dominant exercises to extensively target both hamstrings.

Despite finding high activity for both hamstrings and especially BFlh, there is presently no evidence that advocates that training using these exercises causes sprint-specific adaptations in the muscles, let alone reduces risk for HMI. For that, it will be necessary to investigate whether closed kinetic chain hip-dominant exercises improve horizontal force production and further if they impact known risk factors for HMI.

CONCLUSION

This study presented EMG data that shows that the three hip-dominant exercises exert high amounts of hamstring muscle activity that reaches and even surpasses those seen during the NHE. Additionally, GMax activity played a leading role in hip extension whereby hamstring selectivity of the exercises is still uncertain. The hip and knee flexion angles of peak muscle activity do partly correspond with treadmill high-speed running. Elongation stress being below zero for all examined exercises poses the possibility for adaptations of hamstring muscles at an unfavorable angle. Nevertheless, the authors suggest that further analysis of the closed kinetic chain hip-dominant exercises and their possible upside of exerting high amounts of hamstring muscle activity be undertaken.

Submitted: November 17, 2023 CDT, Accepted: March 17, 2024 CDT

REFERENCES

1. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *Am J Sports Med*. 2006;34(8):1297-1306. doi:10.1177/0363546505286022

2. Schache AG, Dorn TW, Blanch PD, Brown NAT, Pandy MG. Mechanics of the human hamstring muscles during sprinting. *Med Sci Sports Exerc*. 2012;44(4):647-658. doi:10.1249/mss.0b013e318236a3d2

3. Guex K, Gojanovic B, Millet GP. Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *J Athl Train*. 2012;47(4):390-395. doi:10.4085/1062-6050-47.4.04

4. Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: a systematic review. *Phys Sportsmed*. 2021;51(1):1-19. doi:10.1080/00913847.2021.1992601

5. Forsythe B, Knapik DM, Crawford MD, et al. Incidence of injury for professional soccer players in the United States: A 6-year prospective study of Major League Soccer. *Orthop J Sports Med*. 2022;10(3):23259671211055136. doi:10.1177/23259671211055136

6. Ekstrand J, Bengtsson H, Waldén M, Davison M, Khan KM, Hägglund M. Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: the UEFA Elite Club Injury Study from 2001/02 to 2021/22. *Br J Sports Med*. 2022;57(5):292-298. doi:10.1136/bjsports-2021-105407

7. Okoroha KR, Conte S, Makhni EC, et al. Hamstring injury trends in Major and Minor League Baseball: Epidemiological findings from the Major League Baseball health and injury tracking system. *Orthop J Sports Med*. 2019;7(7):2325967119861064. doi:10.1177/2325967119861064

8. Edouard P, Branco P, Alonso JM. Muscle injury is the principal injury type and hamstring muscle injury is the first injury diagnosis during top-level international athletics championships between 2007 and 2015. *Br J Sports Med*. 2016;50(10):619-630. doi:10.1136/bjsports-2015-095559

9. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. *J Biomech*. 2008;41(15):3121-3126. doi:10.1016/j.jbiomech.2008.09.005

10. Kenneally-Dabrowski CJB, Brown NAT, Lai AKM, Perriman D, Spratford W, Serpell BG. Late swing or early stance? A narrative review of hamstring injury mechanisms during high-speed running. *Scand J Med Sci Sports*. 2019;29(8):1083-1091. doi:10.1111/sms.13437

11. Chumanov ES, Heiderscheit BC, Thelen DG. Hamstring musculotendon dynamics during stance and swing phases of high-speed running. *Med Sci Sports Exerc*. 2011;43(3):525-532. doi:10.1249/mss.0b013e3181f23fe8

12. Chumanov ES, Schache AG, Heiderscheit BC, Thelen DG. Hamstrings are most susceptible to injury during the late swing phase of sprinting. *Br J Sports Med*. 2011;46(2):90. doi:10.1136/bjsports-2011-090176

13. Grange S, Reurink G, Nguyen AQ, et al. Location of hamstring injuries based on magnetic resonance imaging: A systematic review. *Sports Health*. 2022;15(1):111-123. doi:10.1177/19417381211071010

14. Thelen DG, Chumanov ES, Hoerth DM, et al. Hamstring muscle kinematics during treadmill sprinting. *Med Sci Sports Exerc*. 2005;37(1):108-114. doi:10.1249/01.mss.0000150078.79120.c8

15. Schuermans J, Van Tiggelen D, Danneels L, Witvrouw E. Biceps femoris and semitendinosus—teammates or competitors? New insights into hamstring injury mechanisms in male football players: a muscle functional MRI study. *Br J Sports Med*. 2014;48(22):1599-1606. doi:10.1136/bjsports-2014-094017

16. Al Attar WSA, Soomro N, Sinclair PJ, Pappas E, Sanders RH. Effect of injury prevention programs that include the Nordic hamstring exercise on hamstring injury rates in soccer players: a systematic review and meta-analysis. *Sports Med*. 2016;47(5):907-916. doi:10.1007/s40279-016-0638-2

17. 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. doi:10.1136/bjsports-2018-100045

18. Almeida MO, Maher CG, Saragiotto BT. Prevention programmes including Nordic exercises to prevent hamstring injuries in football players (PEDro synthesis). *Br J Sports Med*. 2018;52(13):877-878. doi:10.1136/bjsports-2017-098862

19. Krommes K, Jakobsen MD, Bandholm T, et al. Cross-sectional study of EMG and EMG rise during fast and slow hamstring exercises. *Int J Sports Phys Ther*. 2021;16(4):1033-1042. doi:10.26603/001c.25364

20. Guruhan S, Kafa N, Ecemis ZB, Guzel NA. Muscle activation differences during eccentric hamstring exercises. *Sports Health*. 2020;13(2):181-186. doi:10.1177/1941738120938649

21. Ferri-Caruana A, Mollà-Casanova S, Baquedano-Moreno M, Serra-Añó P. Electromyographic activity of posterior kinetic chain muscles during hamstring strengthening exercises. *Phys Ther Sport*. 2022;55:205-210. doi:10.1016/j.ptsp.2022.04.008

22. Guex K, Millet GP. Conceptual framework for strengthening exercises to prevent hamstring strains. *Sports Med*. 2013;43(12):1207-1215. doi:10.1007/s40279-013-0097-y

23. van den Tillaar R, Solheim JAB, Bencke J. Comparison of hamstring muscle activation during high-speed running and various hamstring strengthening exercises. *Intl J Sports Phys Ther*. 2017;12(5):718-727. doi:10.26603/ijspt20170718

24. Prince C, Morin JB, Mendiguchia J, et al. Sprint specificity of isolated hamstring-strengthening exercises in terms of muscle activity and force production. *Front Sports Act Living*. 2021;2:609636. doi:10.3389/fspor.2020.609636

25. Malliaropoulos N, Panagiotis T, Jurdan M, et al. Muscle and intensity based hamstring exercise classification in elite female track and field athletes: implications for exercise selection during rehabilitation. *Open Access J Sports Med*. 2015;6:209. doi:10.2147/oajsm.s79189

26. Hegyi A, Péter A, Finni T, Cronin NJ. Region-dependent hamstrings activity in Nordic hamstring exercise and stiff-leg deadlift defined with high-density electromyography. *Scand J Med Sci Sports*. 2017;28(3):992-1000. doi:10.1111/sms.13016

27. Bourne MN, Williams MD, Opar DA, Al Najjar A, Kerr GK, Shield AJ. Impact of exercise selection on hamstring muscle activation. *Br J Sports Med*. 2016;51(13):1021-1028. doi:10.1136/bjsports-2015-095739

28. Bourne MN, Timmins RG, Opar DA, et al. An evidence-based framework for strengthening exercises to prevent hamstring injury. *Sports Med*. 2017;48(2):251-267. doi:10.1007/s40279-017-0796-x

29. Albertus-Kajee Y, Tucker R, Derman W, Lamberts RP, Lambert MI. Alternative methods of normalising EMG during running. *J Electromyogr Kinesiol*. 2011;21(4):579-586. doi:10.1016/j.jelekin.2011.03.009

30. Hegyi A, Goncalves BAM, Finni T, Cronin NJ. Individual region- and muscle-specific hamstring activity at different running speeds. *Med Sci Sports Exerc*. 2019;51(11):2274-2285. doi:10.1249/mss.0000000000002060

31. Borg G. *Borg's Perceived Exertion and Pain Scales*. Human kinetics; 1998.

32. Klein-Vogelbach S. *Ballgymnastik Zur Funktionellen Bewegungslehre*. Springer Berlin Heidelberg; 1985. doi:10.1007/978-3-662-05975-3

33. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res*. 1990;8(3):383-392. doi:10.1002/jor.1100080310

34. Jakobsen MD, Sundstrup E, Andersen CH, Persson R, Zebis MK, Andersen LL. Effectiveness of hamstring knee rehabilitation exercise performed in training machine vs. elastic resistance: electromyography evaluation study. *Am J Phys Med Rehabil*. 2014;93(4):320-327. doi:10.1097/phm.0000000000000043

35. Pinto R, Cadore E, Correa C, et al. Relationship between workload and neuromuscular activity in the bench press exercise. *Med Sport*. 2013;17(1):1-6. doi:10.5604/17342260.1041876

36. Šarabon N, Marušič J, Marković G, Kozinc Ž. Kinematic and electromyographic analysis of variations in Nordic hamstring exercise. *PLoS One*. 2019;14(10):e0223437. doi:10.1371/journal.pone.0223437

37. 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. doi:10.2519/jospt.2019.8801

38. Frigo C, Shiavi R. Applications in movement and gait analysis. *Electromyography: Physiology, engineering, and noninvasive applications*. Published online July 12, 2004:381-401. doi:10.1002/0471678384.ch15

39. Shiavi R, Bugle HJ, Limbird T. Electromyographic gait assessment, Part 1: Adult EMG profiles and walking speed. *J Rehabil Res Dev*. 1987;24(2):13-23.

40. Dorn TW, Schache AG, Pandy MG. Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. *J Exp Biol*. 2012;215(11):1944-1956. doi:10.1242/jeb.064527

41. Higashihara A, Nagano Y, Ono T, Fukubayashi T. Relationship between the peak time of hamstring stretch and activation during sprinting. *Eur J Sport Sci*. 2014;16(1):36-41. doi:10.1080/17461391.2014.973913

42. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Architectural adaptations of muscle to training and injury: a narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. *Br J Sports Med*. 2016;50(23):1467-1472. doi:10.1136/bjsports-2015-094881

43. Ono T, Higashihara A, Fukubayashi T. Hamstring functions during hip-extension exercise assessed with electromyography and magnetic resonance imaging. *Res Sports Med*. 2010;19(1):42-52. doi:10.1080/15438627.2011.535769

44. Messer DJ, Bourne MN, Williams MD, Al Najjar A, Shield AJ. Hamstring muscle use in women during hip extension and the Nordic hamstring exercise: A functional magnetic resonance imaging study. *J Orthop Sports Phys Ther*. 2018;48(8):607-612. doi:10.2519/jospt.2018.7748

45. Boyer A, Hug F, Avrillon S, Lacourpaille L. Individual differences in the distribution of activation among the hamstring muscle heads during stiff-leg Deadlift and Nordic hamstring exercises. *J Sports Sci*. 2021;39(16):1830-1837. doi:10.1080/02640414.2021.1899405

46. Hegyi A, Csala D, Péter A, Finni T, Cronin NJ. High-density electromyography activity in various hamstring exercises. *Scand J Med Sci Sports*. 2018;29(1):34-43. doi:10.1111/sms.13303

47. Soga T, Nishiumi D, Furusho A, Akiyama K, Hirose N. Effect of different slopes of the lower leg during the Nordic hamstring exercise on hamstring electromyography activity. *J Sports Sci Med*. 2021;20(2):216-221. doi:10.52082/jssm.2021.216

48. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol*. 2000;10(5):361-374. doi:10.1016/s1050-6411(00)00027-4