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Electromyographic activity of posterior kinetic chain muscles during hamstring strengthening exercises

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A B S T R A C T

Objectives: To compare the muscle activation of the biceps femoris (BF), semitendinosus (ST), gluteus maximus (GM), and contralateral erector spinae (ES) in four specific eccentric hamstring-oriented exercises using overground maximal sprints as an EMG normalization method.
Design: cross-sectional study.
Participants: twenty-four healthy athletes participated in this study.
Main outcome measures: The maximum EMG activation of all targeted muscles was measured during maximal sprints and four hamstring exercises: Nordic hamstring (NH), Russian belt (RB), glider (GL) and lying kick (LK). Maximum EMG activation during sprints were used to normalize EMG muscle activation.
Results: RB and GL showed lower hamstrings activation (from 15.71% to 39.23% and from 26.34% to 31.23%, respectively), so these exercises may be used as the first step of the retraining. The higher hamstring activation was reached in the NH (from 20.15% to 66.81%) and the LK (from 50.5% to 61.2%). Regarding muscles comparison, BF and ST were the most dependent on the exercise ranging from 26.67% to 62.22%, and from 26.34% to 66.81%, respectively.
Conclusions: Muscle activation is dependent on the exercise procedure. RB and GL should be used as a first step because of their low activation. Instead, NH and LK should be used at the last phases of retraining process. Considering the synergistic activation of the PKC muscles during LK, and because of its unilateral and explosive characteristics, LK seems a suitable exercise for retraining PKC muscles in general.

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1. Introduction

Hamstring strain injuries are common in many sports, with high reinjury rates (Orchard et al., 2013), and high speed running accounts for the majority of hamstring strains (Guex & Millet, 2013). In this regard, training the hamstring muscle group is critical for athletic performance and plays an important role in hamstring injury prevention and retraining (Bautista et al., 2021; Burigo et al., 2020; Goode et al., 2015; Ripley et al., 2021; van Dyk et al., 2019; Vatovec et al., 2020). Further, eccentric muscle training has been gaining popularity because it provides a greater increase in muscle strength compared to concentric training (Marušič et al., 2020).

Guex and Millet (2013) concluded that hamstring strength exercises used should be specific to simulate the greater elongation stress of the hamstrings during the late swing phase of sprinting (Guex & Millet, 2013). In this regard, the Nordic hamstring (NH) exercise is the most commonly used exercise for hamstring injury prevention since it has been shown to be effective (Thorborg, 2012; van der Horst et al., 2015), although determining hip flexion angle is important in prescribing this exercise because of its influence on muscles activations (Hegyi, Lahti, et al., 2019). However, NH exercise does not enable eccentric strengthening at hamstring length similar to the length achieved in the late swing phase of the sprinting.

Other exercises such as the Glider (GL), Russian belt (RB) or the Lying kick (LK) are being recommended for hamstring injury prevention in the athletic population because they may better target the hamstring muscles at more specific angles and with higher

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movement velocities that resemble the demands of the late swing in high speed running (Marušič et al., 2020; Severini et al., 2018; van den Tillaar et al., 2017). However, none of the existing studies has directly compared muscle activation in these four specific exercises, all of them accessible, feasible, and non-time-consuming exercises for “on-the-field” strength training.

Regarding to EMG normalization, Chuang and Acker et al. (Chuang & Acker, 2019) recommended sprint running for normalization over maximal voluntary isometric contraction (MVIC) due to its simplicity and also to its ability to produce a larger normalization value since when EMG activation exceed 100% of the normalization method (e.g., when MVIC is used), the muscle activation capacity required to perform a specific task could be underestimated. Further, when normalization values are obtained measuring separate MVICs, each muscle group is required to be activated at different times and a similar intensity level or motivational status cannot be guaranteed between muscle measurements, which is thought to influence the EMG amplitude of MVICs (Albertus-Kajee et al., 2011). Therefore, it seems more appropriate to use sprint running for normalization when studying muscle activation during hamstring exercises.

Van den Tillar et al. (van den Tillaar et al., 2017) found that activation of the hamstring muscles were similar during NH and LK normalizing by the MVIC achieved during sprinting. However, sprinting was performed on a non-motorized treadmill. Since differences in running biomechanics and onset times of muscle activations have been observed between treadmill and overground running (Sedighi et al., 2019) analysis of overground sprinting seems more appropriate to improve ecological validity (Van Caekenberghe et al., 2013).

However, the focus during sport re-education should be placed not only on the hamstring activation level but also on the adequate synergistic functioning (i.e. pattern activation of the muscles during the movement) of the entire posterior kinetic chain (PKC) to protect optimal tissue physiology and to prevent hamstrings from overload during running. Synergistic function is needed to improve functioning characteristics of the hamstring muscles (Maas & Sandercock, 2010). Indeed, Avrillon et al. (Avrillon et al., 2020) observed a lower contribution of the injured biceps femoris to the total knee flexor torque in the injured limb than in the contralateral limb. This decreased contribution was compensated by an increased activation of the semimembranosus muscle.

Therefore, the aim of this study was to compare the maximum muscle activation of the BF, ST and gluteus maximus (GM), and the contralateral erector spinae (ES) in four hamstring-oriented exercises using overground maximal sprinting as an EMG normalization method.

2. Methods

2.1. Study design

The study had a cross-sectional design in which a comparison of the maximum EMG activation of main PKC muscles (i.e., BF, ST, GM and contralateral ES) normalized by the maximum activation of each muscle in a maximal sprint was conducted in four hamstring exercises (i.e. NH, RB, GL and LK). The exercises were chosen based on the results of previous scientific research regarding hamstring muscle activation (Guruhan et al., 2020; Macadam et al., 2015; Marušič et al., 2020; Narouei et al., 2018; Wiesinger et al., 2020a) and focused on targeting the hamstrings in lengthened conditions, which represents the risk situation the hamstrings undergo during the running cycle. To ensure identical positioning of the electrodes, all EMG data were collected in the same session.

2.2. Subjects

Twenty-four healthy and physical active people participated in the study. Eligible participants had to be at least 18 years of age and practice resistance training and sprints regularly (>3 h per week). Exclusion criteria included a history of hamstring injury (i.e., complete or partial muscle rupture, any type of contusion, and/or tendon injury), any lower extremity/low-back injuries, acute or chronic pain in lower body or low back, neurological or vestibular disease, and any exercise contraindication. Participants were asked not to perform any kind of strength or running training during the 48 h before testing.

At the familiarization session, after informing the participants about the study details, they gave written informed consent. Testing procedures were approved by the ethics committee of the University of Valencia (1478064) and performed in accordance with the latest revision of the Declaration of Helsinki.

2.3. Procedures

Seven days before the testing day, volunteers conducted a familiarization session. Moreover, familiarization consisted of assuring that NH, RB, GL and LK were conducted properly. If they were not able to adjust the movement pattern during the session, they had to practice the exercise(s) during the next three days and then come back for another familiarization session.

On the day of the test, all volunteers performed a standardized warm-up. They jogged for an 8-min period at a self-perceived comfortable pace. They further performed dynamic stretches for approximately 8 min (including 3 repetitions for all muscles involved). The warm-up concluded with 2 × 60 m submaximal runs (approximately 80% of maximum perceived sprint speed) and 1 × 60 m maximal run along the running track (3-min rests between runs).

After the standardized warm-up, participants performed 2 × 60 m overground maximal sprints where they were instructed to reach their top speed with 5-min passive rest intervals between sprints. Participants started from a standing start and ran on an artificial turf field with their usual running shoes. To exclude gait changes associated with acceleration during the beginning of the sprint or deceleration at the end of the sprint, participants were instructed to reach their top speed at 20 m and maintain it until the 60 m distance. The muscle activity recorded during the 20 m–50 m were used for EMG normalization. Albertus-Kajee et al. protocol was followed (Albertus-Kajee et al., 2011). After the sprints, participants rested for 5 min before performing one of the four hamstring exercises. The four exercises included the NH, RB, GL and LK. To minimize the effects of the sequence of the exercises, the order of exercises was determined through simple randomization (by choosing from a deck of shuffled cards) for each individual. The subjects received a visual demonstration of each movement prior to the first trial, after which they performed the exercise. Anyone who received more than two corrections, repeated the trial after resting for 5 min and being given corrective feedback from the researcher.

All four exercises were performed with 1 × 5 repetitions and 5-min rests between exercises. The mean of the maximum activation of the three middle repetitions (i.e. 2, 3 and 4) was used to analyse maximum EMG activation. A metronome was set at 60 beats per minute to define the movement speed at the RB and the GL. Metronome was not used for NH and LK because these exercises depend on capacity of volunteer to enhance or stop the movement. Each exercise procedure is explained in the Supplementary Material.

2.4. sEMG measurements

EMG activity (μV) was recorded for the PKC muscles: GM, BF and ST muscles from the dominant leg and contralateral ES, and during overground sprint. Two synchronized portable 2-channel devices coupled with an inertial sensor from the Shimmer branch (Realtime Technologies Ltd, Dublin, Ireland) with a 16-bit analogue/digital (A/D) conversion were used. The sampling frequency was programmed at 1024 Hz. One of the devices registered EMG data from the belly muscles of the contralateral ES and the ipsilateral GM, while the other registered data from the belly muscles of the ipsilateral BF and ST.

The EMG signal was monitored using the mDurance software (MDurance Solutions S.L., Granada, Spain) for Android, previously validated (Hermens et al., 1999) and stored in a cloud coded server for further analysis. The application was installed on a Samsung Galaxy device, model A31 with the Android 10 operating system version (Samsung Group, Seoul, South Korea).

The mDurance software digitally filtered the raw signals automatically through a "Butterworth" band pass filter of the fourth order between 20 and 450 Hz. A cutting frequency for the high-pass of 20 Hz was used to reduce the "artefacts" that could arise during the movement to have minimum impact on the total power recorded by the EMG (Clancy et al., 2002).

It has been shown that a "high-pass" 20 Hz filter offers a better compromise to optimize the information recorded through the EMG (reducing the base noise, suppressing the "artefacts" and minimizing the loss of EMG) compared to 10 and 30 HZ filters (De Luca et al., 2010). The root mean square (RMS) was calculated from a window showing the duration of the eccentric phase of the movement. The three middle repetitions (2nd, 3rd, 4th) of the five performed for each test were used for obtaining the average values of these eccentric phases. The total time of each repetition depended on the exercise and it is described in the supplementary material.

Sensor allocation was conduct before warm-up. First of all, the skin was shaved, rubbed, and cleaned with alcohol. Bipolar pre gelled Ag/AgCl surface electrodes (MedCaT B.V, Doorndistel, Spain, Europe) were then used to record the EMG from these muscles. They were placed in pairs 1.5–2 cm apart and parallel to the muscle fibres. Electrode placement to collect EMG signals from the selected muscles were set following the SENIAM guidelines (Hermens et al., 1999).

Maximum activation (peak EMG) of each muscle during the entire sprint was obtained from the two sprints and the mean of the two maximum values (throughout all the sprint) was used for subsequent normalization of the maximum activation obtained in each exercise (average of the three middle repetitions). Thus, the maximum activation in each exercise was expressed as a percentage of the maximum activation during the sprint.

2.5. Statistics

Statistical data analysis was conducted using SPSS v26 (Inc. IBM., Chicago, IL, USA). Data were presented as mean and standard deviation (SD). A 1-way repeated ANOVA with the within-subjects factor 'hamstring exercise' was used to search for differences in the maximum EMG activation between the four muscles (i.e., BF, ST, GM and ES). Further, a 1-way repeated ANOVA with the within-subjects factor 'muscle' was used to search for differences in the maximum EMG activation between the four exercises. Post-hoc comparisons were performed when significant results were obtained from the ANOVA. Bonferroni correction was performed for that purpose. The type I error was set at 5% ($p \leq 0.05$).

3. Results

3.1. Subjects

The study included 24 healthy sport-playing students (11 male and 13 female; mean (SD) age of 21.5 (2.2) years; weight of 63.9 (10.6) kg and height of 1.72 (0.1) m).

Comparison of the maximum EMG activation of the posterior kinetic chain muscles evaluated during each exercise.

Significant differences in the maximum EMG activation of the muscles analysed were obtained in the NH ($F = 13.05$, $p < 0.01$, $\eta^2 = 0.43$) and the RB ($F = 8.42$, $p < 0.01$, $\eta^2 = 0.31$) exercises. Post hoc comparisons showed that maximum EMG activation of GM was significantly lower in NH than BF and ST. However, for NH there were not significant differences between ES and other muscles. Further, EMG activation of GM was significantly lower in RB than BF, ES and ST. BF and ST showed a similar muscle activation in each exercise (a maximal difference of 4.5%). Fig. 1 shows these differences between muscles for each exercise expressed as a percentage of the maximum EMG activity of the sprint.

3.2. Effect of the exercise on the EMG activation of the four muscles

The maximum EMG activation of each tested muscle significantly differed depending on the exercise performed. Concretely, significant differences were observed for maximum EMG activation of the ES ($F = 6.47$, $p < 0.01$, $\eta^2 = 0.28$), GM ($F = 13.65$, $p < 0.01$, $\eta^2 = 0.41$), BF ($F = 14.52$, $p < 0.01$, $\eta^2 = 0.41$) and ST ($F = 22.40$, $p < 0.01$, $\eta^2 = 0.52$).

Post-hoc comparisons displayed in Fig. 2 show that maximum ES activation was significantly higher in the LK compared to the GL exercise. There were not significant differences on ES activation between RB, GL and LK RB and NH showed similar results to those of the GL. Regarding GM, its maximum activation was significantly higher in the LK compared to the NH, GL and RB exercises. Further, maximum EMG activation of the GM was significantly higher in the GL compared to the RB exercise (Fig. 2). Moreover, maximum activation of the BF and ST were significantly higher in the NH and LK compared to the GL and RB exercises. However, no differences were found for BF and between NH versus LK, and RB versus GL.

4. Discussion

In general, NH and LK showed a higher maximum EMG activation than achieved in the RB and GL.

In our study, all hamstring exercises demanded a PKC muscle (i.e. GM, BF, ST and ES) activation lower than 70% of maximum EMG activation during overground sprint. This results are in line with those of another study (van den Tillaar et al., 2017) in which EMG data of hamstring strength exercises were also normalized by the maximum activation recorded with sprints although performed on a treadmill. It differs in a lower blood lactate concentration on a treadmill than overground, and higher heart rate and rating of perceived exertion during treadmill running was resulted (Miller et al., 2019). Moreover, treadmills running condition caused lower muscle activity consequently, may increase biomechanical efficiency. Therefore, some biomechanical differences were found in knee kinematics, the peak values of ground reaction forces, joint moment, and joint power trajectories (ARSENAULT et al., 1986; Caekenberghe et al., 2013; RILEY et al., 2008; Sedighi et al., 2019).

It seems important to understand PKC muscle activation during hamstring exercises aimed at preventing or rehabilitating hamstring injuries. When comparing the muscle activation for each hamstring exercise, our results show that GM showed lower values

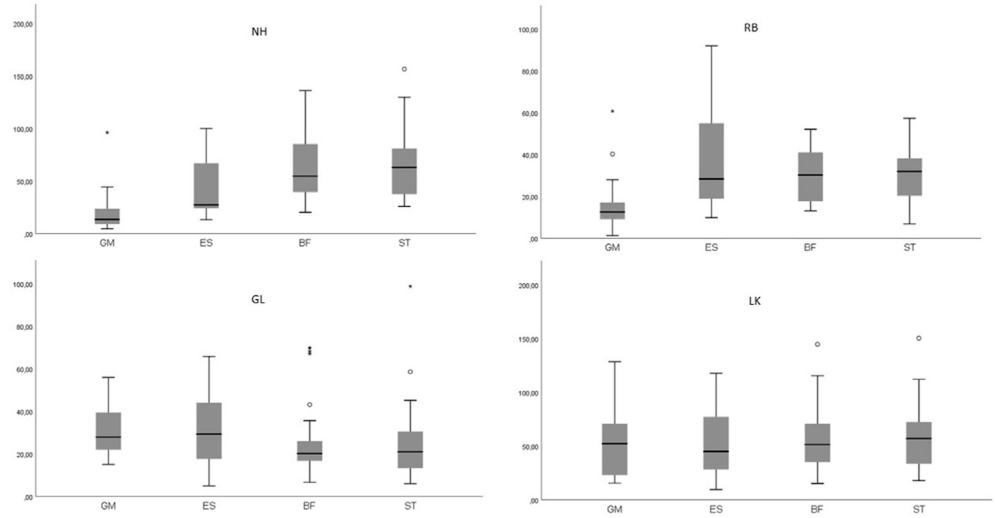

Fig. 1. Maximum EMG activation for gluteus maximus (GM), erector spinae (ES), biceps femoris (BF) and semitendinosus (ST) muscles during the four exercises (%) normalized by the maximum activation during sprint. NH: Nordic hamstring; RB: Russian belt; GL: Glider; LK: Lying kick.

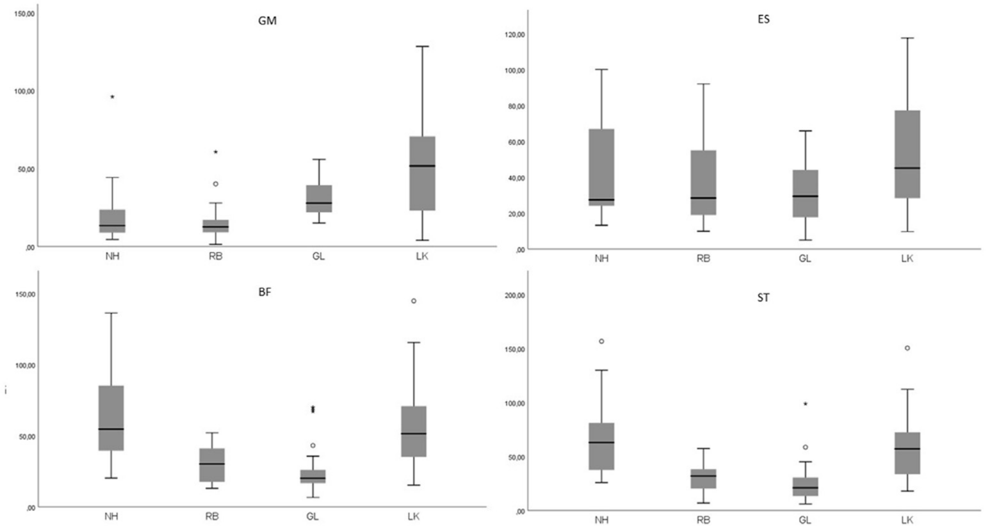

Fig. 2. Normalized maximum EMG activation (%) of each muscle group in each hamstring exercise. NH: Nordic hamstring; RB: Russian belt; GL: Glider; LK: Lying kick; GM: gluteus maximus; ES: erector spinae; BF: biceps femoris; ST: semitendinosus.

of muscle activity during NH compared to BF and ST. This outcome may rely on the exercise procedure being a knee-dominant exercise, therefore requesting greater activation of the knee flexion muscles. It was found (Šarabon et al., 2019; Wiesinger et al., 2020b) that the differences between GM activation and hamstring activation during NH were between 50% and 72%, GM activation being lower. In our study, these differences were in the same line but with a lower magnitude, probably due to the fact that, relative to hamstrings, GM activation might be greater during overground sprints than during MVIC (Okkonen & Häkkinen, 2013). We should take into consideration that variations of this exercise including different hip positions could influence the results. Therefore, future studies should explore muscle activation with different procedures to determine the most suitable exercise. Accordingly, RB exercise also showed a lower GM activation compared to the other PKC muscles. This is an outstanding result since RB is a hip extension-oriented exercise. Indeed, Neto et al. (Neto et al., 2020a) found high levels of GM activation for the stiff-leg deadlift exercise, another hip extension-oriented exercise. The pace, lack of external load, level of fatigue the mechanical complexity of the exercise, the hip angulation and therefore the need for joint stabilization, might directly jeopardize GM activation (Neto et al., 2020b). Therefore, our study provides evidence that the RB exercise, despite being a hip extension-oriented exercise, does not guarantee high GM activation. Accordingly, this is contrary to the standard practice of prescribing RB to train GM (Neto et al., 2020b), and other types of exercise might be more appropriate for that purpose.

The relatively low contribution of the GM as compared to other PKC muscles during both RB and NH suggests that a complementary strength exercise focused on GM may be necessary to elicit a compensatory muscle activation in the PKC. This is specially so in those athletes with an altered “pelvic balance” (i.e. hamstring synergistic dominance at hip extension or anterior pelvic tilt) (Sahrmann et al., 2017). Conversely, the exercise which most activates GM is LK, probably because of the unilateral and explosive procedure involved, since subject performed a fast and hard kick into the air triggering the hips and the foot of the supporting leg to lift from the floor.

With regard to ES, its activation was higher than that of the GM both in RB and NH, (although no significant level was achieved in NH [difference of 20.60; p = 0.055]). Probably because these, the role of ES in these exercises is to maintain a neutral spine and trunk angle, since it is the chief extensor in the vertebral column and it collaborates in maintaining lumbar curve (Tortora & Derrickson, 2017). In this line, Narouei et al. (Narouei et al., 2018) and Park et al. (Park et al., 2019) found that ES was more greatly activated than GM during NH (). In the case of RB exercise, the difference between ES and GM activation was 25.27%. However, ES activation between exercises did not differ. Holding the upper body load in a forward bended position may place a high demand of activation on the ES, similar to that of the hamstring muscles.

In our study, no significant differences between PKC muscle activation were obtained in the GL, this being consistent with the results obtained by Severini et al. (Severini et al., 2018). Therefore, GL is an exercise that facilitates the synergistic cooperation of the PKC muscles. However, this exercise does not allow a high level of activation of the PKC muscles (all activated under 35%, probably due to the fact that during the RB, NHE and LK the hamstrings are activated to resist the fall of the upper body out of the base of support, while in the GL, they resist the sliding of the leg maintaining the upper body center of mass inside the base of support, so an increase in intensity should be recommended in order to reach higher levels of muscle activation. In line with this, LK also showed no significant differences between PKC muscles. Nevertheless, in this exercise, activation of all the muscles is around 50–60%. Both exercises need to be performed in a unilateral way. This may explain the lack of differences between GM and hamstrings (i.e. BF and ST). Indeed, an important role of the GM in pelvic and spinal stabilization during load transfer has been found in unilateral weight-bearing exercises such as the step-up exercise (Macadam et al., 2015). Therefore, the LK exercise seems an appropriate exercise to activate the GM muscle due to its unilateral and explosive hip extension pattern. However, these results could change in case of adding different loads. More studies are needed to assess differences in activation during this exercise depending on external load used. Finally, BF and ST showed a similar muscle activation in each exercise (1.48–4.01% of difference). In line with our results, Hegyi et al. (Hegyi, Csala, et al., 2019) have reported similar ST and BF activation during all the exercises tested. BF and ST could act in all exercises because they intervene in hip and knee joints and all exercise includes both joints. However, this information should be taken with caution due to the method used for normalization.

Regarding exercise intensity, RB and GL showed an overall significantly lower muscle activation than NH and LK. Therefore, these exercises could be introduced at an earlier stage of the hamstring exercise rehabilitation. NH would then be recommended, also taking into consideration the low demand on ES and GM muscle stabilization and its analytic focus on hamstring muscles. The prescription of LK, therefore, should be placed at more advanced stages because of its complexity and its high demands on hamstring, GM and ES muscles. It should be noted that all these exercises were performed without external loads so results including different loads could modify these results. Further studies should be needed to investigate the effect of external loads on muscle activity. There were some limitations to this study since all participants were active healthy individuals; thus our results could not be extrapolated to a sedentary population (because sedentary behaviour negatively influences functional tasks (i. e., strength production capacity and walking (van der Velde et al., 2017)). Moreover, there will always be a possibility of cross-talk in neighbouring muscles when using surface EMG (Farina et al., 2004).

Activation strategies not only vary between individuals, but are unique to each individual (Hug et al., 2010). Our results support this idea as shown by the large standard deviations obtained. Therefore, individual differences must be considered when programming NH and LK exercises to improve performance and/or prevent injury. Future studies could analyse the activation of the muscles in other types of exercises that were not static and therefore see its relationship with dynamic exercise, like sprint.

5. Conclusions

We provide evidence that the activation of PKC muscles involved in common hamstring exercises is less than 70% of maximum EMG activity during overground sprint.

Proper exercise selection is a basic component of the retraining program for hamstring injuries. In this regard, and based on the extent of muscle activation of the exercises analysed, RB and GL should be performed as a first step in retraining. Considering the synergistic activation of the PKC muscles during LK, and because of its unilateral and explosive characteristics, LK seems a suitable exercise for retraining PKC muscles in general. NH is the exercise obtaining greater activation of the hamstrings, so this is an appropriate exercise to focus on hamstring retraining at more advanced stages; however, due to the low level of GM activation, an additional strength exercise focused on GM is recommended.

Declaration of competing interest

No conflicts of interest, financial or otherwise, are declared by the authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2022.04.008.

References

Albertus-Kajee, Y., Tucker, R., Derman, W., Lamberts, R. P., & Lambert, M. I. (2011). Alternative methods of normalising EMG during running. *Journal of Electromyography and Kinesiology, 21*, 579–586.

Arsenault, A. B., Winter, D. A., & Marteniuk, R. G. (1986). Treadmill versus walkway locomotion in humans: An EMG study. *Null, 29*, 665–676. https://doi.org/10.1080/00140138608968301

Avrillon, S., Hug, F., & Guilhem, G. (2020). Bilateral differences in hamstring coordination in previously injured elite athletes. *Journal of Applied Physiology, 128*, 688–697. https://doi.org/10.1152/japplphysiol.00411.2019

Bautista, I., Vicente-Mampel, J., Baraja, L., Segarra Nuñez, V., Martin-Rivera, F., & Hooren, B. (2021). The effects of the nordic hamstring exercise on sprint performance and eccentric knee flexor strength: A systematic review and meta-analysis of intervention studies among team sport players. *Journal of Science and Medicine in Sport, 24*. https://doi.org/10.1016/j.jsams.2021.03.009

Burigo, R. L., Scoz, R. D., Alves, B. M. de O., da Silva, R. A., Melo-Silva, C. A., Vieira, E. R., Hirata, R. P., & Amorim, C. F. (2020). Concentric and eccentric isokinetic hamstring injury risk among 582 professional elite soccer players: A 10-years retrospective cohort study. *BMJ Open Sport Exercise Medicine, 6*, Article e000868. https://doi.org/10.1136/bmjsem-2020-000868. e000868.

Caekenberghe, I. V., Segers, V., Aerts, P., Willems, P., & De Clercq, D. (2013). Joint kinematics and kinetics of overground accelerated running versus running on an accelerated treadmill. *Journal of The Royal Society Interface, 10*, Article 20130222. https://doi.org/10.1098/rsif.2013.0222, 20130222.

Chuang, T. D., & Acker, S. M. (2019). Comparing functional dynamic normalization methods to maximal voluntary isometric contractions for lower limb EMG from walking, cycling and running. *Journal of Electromyography and Kinesiology, 44*, 86–93.

Clancy, E. A., Morin, E. L., & Merletti, R. (2002). Sampling, noise-reduction and amplitude estimation issues in surface electromyography. *Journal of Electromyography and Kinesiology, 12*, 1–16.

De Luca, C. J., Gilmore, L. D., Kuznetsov, M., & Roy, S. H. (2010). Filtering the surface EMG signal: Movement artifact and baseline noise contamination. *Journal of Biomechanics, 43*, 1573–1579.

van Dyk, N., Behan, F. P., & Whiteley, R. (2019). Including the nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries:

A systematic review and meta-analysis of 8459 athletes. *British Journal of Sports Medicine, 53*, 1362. https://doi.org/10.1136/bjsports-2018-100045

Farina, D., Merletti, R., & Enoka, R. M. (2004). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology, 96*, 1486–1495.

Goode, A. P., Reiman, M. P., Harris, L., DeLisa, L., Kauffman, A., Beltramo, D., Poole, C., Ledbetter, L., & Taylor, A. B. (2015). Eccentric training for prevention of hamstring injuries may depend on intervention compliance: A systematic review and meta-analysis. *British Journal of Sports Medicine, 49*, 349. https://doi.org/10.1136/bjsports-2014-093466

Guex, K., & Millet, G. P. (2013). Conceptual framework for strengthening exercises to prevent hamstring strains. *Sports Medicine, 43*, 1207–1215.

Guruhan, S., Kafa, N., Ecemis, Z. B., & Guzel, N. A. (2020). Muscle activation differences during eccentric hamstring exercises. *Sport Health, 13*(2), 181–186. https://doi.org/10.1177/1941738120938649

Hegyi, A., Csala, D., Péter, A., Finni, T., & Cronin, N. J. (2019a). High-density electromyography activity in various hamstring exercises. *Scandinavian Journal of Medicine & Science in Sports, 29*, 34–43.

Hegyi, A., Lahti, J., Giacomo, J.-P., Gerus, P., Cronin, N. J., & Morin, J.-B. (2019b). Impact of hip flexion angle on unilateral and bilateral nordic hamstring exercise torque and high-density electromyography activity. *Journal of Orthopaedic & Sports Physical Therapy, 49*, 584–592. https://doi.org/10.2519/jospt.2019.8801

Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., Disselhorst-Klug, C., & Hägg, G. (1999). European recommendations for surface electromyography. *Roessingh Research and Development, 8*, 13–54.

van der Horst, N., Smits, D.-W., Petersen, J., Goedhart, E. A., & Backx, F. J. (2015). The preventive effect of the nordic hamstring exercise on hamstring injuries in amateur soccer players: A randomized controlled trial. *The American Journal of Sports Medicine, 43*, 1316–1323.

Hug, F., Turpin, N. A., Guével, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? *Journal of Applied Physiology, 108*, 1727–1736.

Maas, H., & Sandercock, T. G. (2010). Force transmission between synergistic skeletal muscles through connective tissue linkages. *Journal of Biomedicine and Biotechnology.* , Article 575672. https://doi.org/10.1155/2010/575672, 2010.

Macadam, P., Cronin, J., & Contreras, B. (2015). An examination of the gluteal muscle activity associated with dynamic hip abduction and hip external rotation exercise: A systematic review. *International Journal of Sports Physical Therapy, 10*, 573.

Marušič, J., Vatovec, R., Marković, G., & Šarabon, N. (2020). Effects of eccentric training at long-muscle length on architectural and functional characteristics of the hamstrings. *Scandinavian Journal of Medicine & Science in Sports, 30*, 2130–2142.

Miller, J. R., Van Hooren, B., Bishop, C., Buckley, J. D., Willy, R. W., & Fuller, J. T. (2019). A systematic review and meta-analysis of crossover studies comparing physiological, perceptual and performance Measures between treadmill and overground running. *Sports Medicine, 49*, 763–782. https://doi.org/10.1007/s40279-019-01087-9

Narouei, S., Imai, A., Akuzawa, H., Hasebe, K., & Kaneoka, K. (2018). Hip and trunk muscles activity during nordic hamstring exercise. *Journal of Exercise Rehabilitation, 14*, 231.

Neto, W. K., Soares, E. G., Vieira, T. L., Aguiar, R., Chola, T. A., de Lima Sampaio, V., & Gama, E. F. (2020a). Gluteus maximus activation during common strength and hypertrophy exercises: A systematic review. *Journal of Sports Science and Medicine, 19*, 195.

Neto, W. K., Soares, E. G., Vieira, T. L., Aguiar, R., Chola, T. A., de Lima Sampaio, V., & Gama, E. F. (2020b). Gluteus maximus activation during common strength and hypertrophy exercises: A systematic review. *Journal of Sports Science and Medicine, 19*, 195.

Okkonen, O., & Häkkinen, K. (2013). Biomechanical comparison between sprint start, sled pulling, and selected squat-type exercises. *The Journal of Strength & Conditioning Research, 27*, 2662–2673.

Orchard, J. W., Seward, H., & Orchard, J. J. (2013). Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *The American Journal of Sports Medicine, 41*, 734–741.

Park, S.-Y., Kim, S.-H., & Park, D.-J. (2019). Effect of slope angle on muscle activity during variations of the Nordic exercise. *Journal of Exercise Rehabilitation, 15*, 832.

Riley, P. O., Dicharry, J., Franz, J., Croce, U. D., Wilder, R. P., & Kerrigan, D. C. (2008). A kinematics and kinetic comparison of overground and treadmill running. *Medicine & Science in Sports & Exercise, 40*.

Ripley, N. J., Cuthbert, M., Ross, S., Comfort, P., & McMahon, J. J. (2021). The effect of exercise compliance on risk reduction for hamstring strain injury: A systematic review and meta-analyses. *International Journal of Environmental Research and Public Health, 18*. https://doi.org/10.3390/ijerph182111260

Sahrmann, S., Azevedo, D. C., & Van Dillen, L. (2017). Diagnosis and treatment of movement system impairment syndromes. *Brazilian Journal of Physical Therapy, 21*, 391–399.

Šarabon, N., Marušič, J., Marković, G., & Kozinc, Ž. (2019). Kinematic and electromyographic analysis of variations in Nordic hamstring exercise. *PLoS One, 14*, Article e0223437.

Sedighi, A. R., Anbarian, M., & Ghasemi, M. H. (2019). Comparison of the electromyography activity of selected leg-dominant lower limb muscles during stance phase of running on treadmill and overground. *Turkish Journal of Sport and Exercise, 21*, 46–51. https://doi.org/10.15314/tsed.467735

Severini, G., Holland, D., Drumgoole, A., Delahunt, E., & Ditroilo, M. (2018). Kinematic and electromyographic analysis of the Askling L-Protocol for hamstring training. *Scandinavian Journal of Medicine & Science in Sports, 28*, 2536–2546.

Thorborg, K. (2012). *Why hamstring eccentrics are hamstring essentials*. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine.

van den Tillaar, R., Solheim, J. A. B., & Bencke, J. (2017). Comparison of hamstring muscle activation during high-speed running and various hamstring strengthening exercises. *International Journal of Sports Physical Therapy, 12*, 718.

Tortora, G. J., & Derrickson, B. (2017). Principles of anatomy & physiology/gerard J. Tortora, bryan Derrickson. In *Tortora's Principles of anatomy and physiology* (15th ed.). Hoboken, NJ: Wiley. Global edition.

Van Caekenberghe, I., Segers, V., Willems, P., Gosseye, T., Aerts, P., & De Clercq, D. (2013). Mechanics of overground accelerated running vs. running on an accelerated treadmill. *Gait & Posture, 38*, 125–131.

Vatovec, R., Kozinc, Ž., & Šarabon, N. (2020). Exercise interventions to prevent hamstring injuries in athletes: A systematic review and meta-analysis. *Null, 20*, 992–1004. https://doi.org/10.1080/17461391.2019.1689300

van der Velde, J. H. P. M., Savelberg, H. H. C. M., van der Berg, J. D., Sep, S. J. S., van der Kallen, C. J. H., Dagnelie, P. C., Schram, M. T., Henry, R. M. A., Reijven, P. L. M., van Geel, T. A. C. M., Stehouwer, C. D. A., Koster, A., & Schaper, N. C. (2017). Sedentary behavior is only marginally associated with physical function in adults aged 40–75 Years—the maastricht study. *Frontiers in Physiology, 8*.

Wiesinger, H.-P., Gressenbauer, C., Kösters, A., Scharinger, M., & Müller, E. (2020a). Device and method matter: A critical evaluation of eccentric hamstring muscle strength assessments. *Scandinavian Journal of Medicine & Science in Sports, 30*, 217–226.

Wiesinger, H.-P., Gressenbauer, C., Kösters, A., Scharinger, M., & Müller, E. (2020b). Device and method matter: A critical evaluation of eccentric hamstring muscle strength assessments. *Scandinavian Journal of Medicine & Science in Sports, 30*, 217–226.