Effect of Nordic Hamstring Exercise Training on Knee Flexors Eccentric Strength and Fascicle Length: A Systematic Review and Meta-Analysis

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Context: Nordic hamstring exercise (NHE) has been widely employed to prevent hamstring strain injuries. However, it is still not clear which adaptations are responsible for the NHE preventive effects. **Objectives:** The aim of this study was to investigate the effects of NHE on knee flexors eccentric strength and fascicle length. **Evidence Acquisition:** The search strategy included MEDLINE, PEDro, and Cochrane CENTRAL from inception to April 2020. Randomized clinical trials that have analyzed the effects of NHE training on hamstring eccentric strength and/or fascicle length were included. **Evidence Synthesis:** From the 1932 studies identified, 12 were included in the systematic review, and 9 studies presented suitable data for the meta-analysis. All studies demonstrated strength increments in response to NHE training (10%–15% and 16%–26% in tests performed on the isokinetic dynamometer and on the NHE device, respectively), as well as significant enhancement of biceps femoris long head fascicle length (12%–22%). Meta-analysis showed NHE training was effective to increase knee flexors eccentric strength assessed with both isokinetic tests (0.68; 95% confidence interval, 0.29 to 1.06) and NHE tests (1.11; 95% confidence interval, 0.62 to 1.61). NHE training was also effective to increase fascicle length (0.97; 95% confidence interval, 0.46 to 1.48). **Conclusions:** NHE training has the potential of increasing both knee flexors eccentric strength and biceps femoris long head fascicle length.

Keywords: posterior thigh, hamstring strength, hamstring strain injury, injury prevention

Muscle injuries have a high incidence in sports that involve high-speed movements¹ such as track and field,² rugby,³ basketball,⁴ soccer,⁵ and American football,⁶ as well as in ballet dancers.⁷ Muscle injuries are responsible for 10% to 55% of all injuries in sport,^{5,8–10} and they are common at the high school,¹¹ college,^{12,13} and professional levels.⁵ About 92% of all lower limb muscle injuries affect hamstrings, adductors, quadriceps, or calf (gastrocnemius and/or soleus), and the hamstring muscles are the most commonly injured.¹⁴ Most of hamstring strain injuries (HSI) are considered of moderate severity (54%), with the athlete losing 17 days of practice on average.¹⁵ However, 15% of HSI are severe, which usually requires a longer rehabilitation period (>28-d lay-off).¹⁵ Furthermore, the reinjury rate of HSI is relatively high, especially when it affects the biceps femoris (18.4%).¹⁶ Consequently, HSI impairs athletes' performance,¹⁷ and it has negative financial consequences for the club involved.^{18,19}

With the aim of avoiding all the deleterious effects of an HSI, many studies^{20–26} have concentrated their efforts in identifying risk factors for HSI in an attempt to contribute to the development of prevention programs. The risk factors can be divided in nonmodifiable (eg, previous injuries, age, and genetics) and modifiable (eg, flexibility, fatigue, eccentric strength, and fascicle length).^{27,28} Knee flexors eccentric strength^{29–31} and biceps femoris fascicle length^{29,32,33} have received great attention in the last decade. For instance, a prospective cohort study²⁹ evidenced that elite soccer players with knee flexors eccentric weakness (<337 N assessed with the NordBord System³⁴) and short biceps femoris long head

fascicle length (<10.56 cm) were 4.4 and 4.1 times more likely to sustain an HSI, respectively. Therefore, strategies capable of increasing both eccentric strength and fascicle length seem to be crucial to decrease risk of HSI.

Resistance training is conventionally performed with the same external load during the concentric and eccentric phases, but studies with different populations have demonstrated higher increments in muscle strength through eccentric overload training.^{35–38} Eccentric training also seems to generate greater strength gains than concentric training.³⁹ Whereas concentric training presents small or nonsignificant impact on either muscle eccentric strength³⁹ or fascicle length,⁴⁰ training programs with eccentric overload seem to increase both eccentric strength and fascicle length.^{41,42} In fact, eccentric exercise has been suggested as an effective strategy to prevent HSI,^{20,24} and the Nordic hamstring exercise (NHE) is increasingly popular among athletes and coaching/medical staffs.^{43,44}

Studies have shown that NHE-based training has the potential to reduce HSI rate in athletes of baseball,²⁵ rugby,³ and soccer,^{20,22,24,45} and this preventive effect of NHE is further supported by a recent meta-analysis,⁴⁶ which identified that NHE is capable of decreasing in 50% the incidence of HSI. In face of the promising results of NHE as a preventive strategy against the HSI in athletes, clarifying the mechanisms responsible for the preventive effect of this resistance exercise with eccentric emphasis is pertinent. Hence, this systematic review and meta-analysis aims to analyze the effects of NHE on knee flexors eccentric strength and fascicle length.

Evidence Acquisition

The current study utilized PRISMA (Preferred Reporting Items for Systematic Review and Meta-analyses) guidelines for

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systematic reviews and meta-analysis.⁴⁷ Prior to search, a review protocol was completed and registered at PROSPERO (CRD42018092699).

Data Sources and Searches

We searched the following electronic databases (from inception to April 2020): MEDLINE (accessed by PubMed), Physiotherapy Evidence Database (PEDro), and The Cochrane Central Register of Controlled Trials (Cochrane CENTRAL). In addition, we searched the references of published studies. Retrieved references were imported into EndNote X7 (Thomson Reuters, New York City, NY), where duplicates were subsequently deleted. The search comprised the following terms: “Hamstring Muscle,” “Semitendinosus,” “Semimembranosus,” “Biceps Femoris,” “Posterior thigh,” “Muscle architecture,” “Fascicle length,” “Pennation angle,” “Muscle thickness,” “Nordic hamstring exercise,” “Nordic curl,” “Nordic curl exercise,” and “Hamstring injury prevention,” combined with a high-sensitivity combination of words used in the search for randomized clinical trials.⁴⁸ We included only publications in English. For the combination of the keywords, we utilized the Boolean terms “AND” and “OR.”

Eligibility Criteria

We included randomized clinical trials and controlled clinical trials that evaluated the effects of NHE on eccentric strength and/or fascicle length. In order to improve the clarity of the information provided, the term “strength” will be used to refer the muscle ability to produce force. The following exclusion criteria were used: (1) samples comprised of people with any disease/dysfunction, (2) nonapplication of NHE, (3) nonevaluation of hamstring eccentric strength or fascicle length, (4) application of NHE in association with other exercises, (5) noninclusion of a control group (CG), (6) samples with mean age under 18 years old, and (7) studies with training protocol shorter than 4 weeks or 8 sessions. It should be mentioned that we chose to include participants of both genders because our analyses considered the difference between preintervention and postintervention whether than the peak values. Even though women might present lower peak torque when compared with men,⁴⁹ the adaptations observed after training tend to be similar. As for fascicle length, a recent investigation has shown that fascicle length does not differ between sexes.⁵⁰ Thus, the inclusion of both male and female participants is unlikely to affect our results.

Studies Selection and Data Extraction

Two investigators independently evaluated titles and abstracts of all articles identified by the search strategy. All abstracts that did not provide sufficient information regarding the inclusion and exclusion criteria were selected for full-text evaluation. In the second phase, the same reviewers independently evaluated the full-text articles and made their selection in accordance with the eligibility criteria. Disagreements between reviewers were solved by consensus. Using standardized forms, the same 2 reviewers independently conducted data extraction with regard to the methodological characteristics of the studies, number of participants, age, NHE training protocol, outcomes assessments, and results. Disagreements were also solved by consensus. The outcomes extracted were knee flexors eccentric strength (peak force or peak torque) and muscular fascicle length. It is important to highlight that the eccentric peak torque was evaluated by isokinetic

dynamometry, while eccentric peak force was assessed during an NHE execution through specific devices with load cells.

Quality Assessment

The methodological quality of each study was independently assessed by 2 investigators, and any discrepancies were resolved by consensus. The quality and risk of bias were evaluated according to the Cochrane risk of bias tool,⁵¹ where 4 main domains of bias are assessed: selection bias, detection bias, attrition bias, and reporting bias. Studies without a clear description of these characteristics were considered unclear.

Data Synthesis and Analysis

Intervention effects for strength and fascicle length were calculated using standardized mean differences (SMDs) with 95% confidence intervals (CIs), as all data were continuous. The mean change scores and SDs of the change scores from the intervention and CGs were used to calculate the SMD. If the SDs of the change scores were not reported, these were calculated using the formula,⁵² where correlation coefficients were conservatively set at .5.⁵³ A positive SMD represents an effect in favor of intervention group and a negative SMD an effect in favor of CG. Statistical heterogeneity of the treatment effects among studies was assessed using Cochran Q test and the inconsistency I^2 test, in which values above 25% and 50% were considered indicative of moderate and high heterogeneity, respectively.⁵⁴ A random effects model was selected for the analysis. All analyses were conducted using Review Manager (version 5.3; London, United Kingdom). For the studies that reported only standard error, we estimated the SD by multiplying the standard error by the square root of the sample size (n). For the studies that presented the values of torque in Newton meter per kilogram,^{55,56} we multiplied the values by the mean weight of the subjects in order to normalize the results and perform a more complete analysis. Furthermore, it is important to point out that for the study that presented its data only through graphs,⁵⁷ the values were extracted using the Plot Digitizer.⁵⁸ We explored heterogeneity between studies by rerunning the meta-analyses removing one paper at a time to check whether some individual study explained heterogeneity.

Evidence Synthesis

Description of Studies

The search strategy yielded 1932 articles, after the exclusion of the duplicates (560 studies) identified by the software Endnote; 1377 titles were analyzed, of which 29 studies were considered as potentially relevant and retrieved for detailed analysis. In the full-text analysis, 17 studies were excluded. Hence, 12 studies met the eligibility criteria and were included in the systematic review ($n = 299$), and 9 studies presented suitable data for meta-analysis ($n = 205$). Figure 1 shows the flow diagram of the studies included in this review, and Table 1 summarizes the studies' characteristics and their main results.

Risk of Bias

Of the studies included in this systematic review, 50% presented an adequate sequence generation, 25% reported allocation concealment; 58% had blinded assessment of outcomes, 58% described losses to follow-up and exclusions, and none of the included studies had incomplete outcome data or selectively reported the outcomes (Table 2).

Figure 1 — Flowchart of the included studies. NHE indicates Nordic hamstring exercise.

Effects of NHE on Eccentric Strength

Eleven studies evaluated the effects of NHE on eccentric strength (peak torque or force).^{56,57,59–63,65–68} Eight studies presented suitable data for meta-analysis. Analysis of studies that evaluated eccentric peak torque^{55,56,59,61,66} showed a significant difference between NHE and CG (0.68; 95% CI, 0.29 to 1.06; I^2 : 0%; Figure 2). Analysis of studies that assessed eccentric peak force^{57,62,67} also showed a significant difference between NHE and CG (0.11; 95% CI, 0.62 to 1.61; I^2 : 55%; Figure 3). The high heterogeneity in the latter analysis can be explained by the study from Bourne et al.⁵⁷ that worked with a different population when compared with the studies from Ishøi et al.⁶² and Suarez-Arrones et al.⁶⁷ It is reasonable to assume that the participants' physical conditioning differences (active male vs soccer players) may have played a role in the difference in the adaptations found. When the study from Bourne et al.⁵⁷ was excluded from the meta-analysis, the heterogeneity was 0% (0.88; 95% CI, 0.33 to 1.42; I^2 : 0%).

Effects of NHE on Fascicle Length

Five studies^{56,57,63,64,66} evaluated the effects of NHE on biceps femoris long head fascicle length. All of them compared NHE with a CG (no intervention or alternative exercise). Four studies^{56,57,64,66} provided suitable data for meta-analysis. The analysis showed that

NHE is effective in increasing fascicle length when compared with a CG (0.97; 95% CI, 0.46 to 1.48; I^2 : 71%; Figure 4). The high heterogeneity in the analysis of fascicle length can once again be explained by the study from Bourne et al.⁵⁷ The authors performed a longer NHE training (10 wk) when compared with the other studies (4⁶⁶ and 6 wk^{56,64}). It is possible that the longer training period might have contributed to the higher increase in fascicle length observed by Bourne et al.⁵⁷ When this study was excluded from the meta-analysis, the heterogeneity was 0% (0.65; 95% CI, 0.09 to 1.20; I^2 : 0%).

Discussion

Summary of Evidence

The evidence presented in the current review showed that NHE-based training has the potential to enhance both HSI risk factors assessed in this review: knee flexors eccentric strength and biceps femoris long head fascicle length.

Effects of NHE on Strength

Hamstring muscles have a fundamental role on sprinting, especially during the terminal swing phase, when there is an intense

Table 1 Characteristics of the Included Studies

Study	Groups	Mean age (SD)	NHE training program	Outcomes	Results for hamstring eccentric strength	Results for BFlh fascicle length
Bourne et al ⁵⁷	30 active males NHE: 10 NHE: 10 CG: 10	HE: 23.1 (4.1) NHE: 21.6 (3.2) CG: 21.3 (3.7)	2–5 × 6–10 repetitions 2 times per week 10 wk	ECC strength (during NHE) BFsh and ST architecture: FL, ACSA, and VOL	NHE: +26.3% CG: no change	NHE: +20.5% CG: no change
Delahunt et al ⁵⁹	29 active males NHE: 15 CG: 14	22 (1.38)	2–3 × 5–12 repetitions 1–3 times per week 6 wk	ECC MVC (120 deg/s) EMG activity	NHE: +15.2% CG: no change	NA
Delextrat et al ⁶⁰	30 female hockey players NHE: 10 HC: 10 CG: 10	NHE: 19.7 (1.4) HC: 19.5 (1.0) CG: 19.6 (1.4)	2–3 × 6–10 repetitions 3 times per week 6 wk	ECC PT (120 deg/s)	NHE: 12.4% HC: 7.1% CG: –4.5%	NA
Iga et al ⁶¹	18 male soccer players NHE: 10 CG: 8	NHE: 23.4 (3.3) CG: 22.3 (3.9)	2–3 × 5–8 repetitions 1–3 times per week 4 wk	ECC PT (60, 120, and 240 deg/s) EMG activity	NHE: +15% CG: no change	NA
Ishøi et al ⁶²	35 male soccer players NHE: 18 CG: 17	NHE: 19.1 (1.8) CG: 19.4 (2.1)	1–3 × 5–12 repetitions 1–3 times per week 10 wk	ECC strength (during NHE) RSA 10-m sprint	NHE: +19.2% CG: no change	NA
Lovell et al ⁶³	42 male amateur soccer players CG: 12 NHE before: 14 NHE after: 16	23.6 (4.7)	2–4 × 5–12 repetitions 1–2 times per week 12 wk	ECC PT BFlh architecture: FL, MT, and PA EMG activity	NHE: +11.9% CG: no change	NHE: +12.9% CG: no change
Mendiguchia et al ⁶⁴	32 soccer players	Not informed	2–3 × 5–12 repetitions 1–3 times per week 6 wk	BFlh architecture: FL, MT, and PA Sprint performance	NA	NHE: 7.4% CG: –0.2%
Mjølsnes et al ⁶⁵	21 well-trained male soccer players NHE: 11 HC: 10	Not informed	2–3 × 5–12 repetitions 1–3 times per week 10 wk	ECC (60 deg/s) and ISO PT H:Q ratio Flexibility	NHE: +11% CG: no change	NA
Ribeiro-Alvares et al ⁶⁶	14 active females and 6 active males	NHE: 23.7 (3.3) CG: 26.0 (2.7)	3 × 6–10 repetitions 2 times per week 4 wk	CON and ECC PT (60 deg/s) H:Q ratio BFlh architecture: FL, MT, and PA Flexibility	NHE: +14.5% CG: no change	NHE: +22% CG: no change
Salci et al ⁵⁵	25 recreational female athletes NHE: 13 CG: 12	NHE: 20.5 (1.2) CON: 21.0 (1.6)	2–3 × 5–12 repetitions 1–3 times per week 10 wk	ECC and CON PT (60 deg/s)	NHE: +10% CG: no change	NA
Seymore et al ⁵⁶	20 adults: 6 males and 14 females NHE: 10 CG: 10	NHE: 18.3 (0.5) CON: 19.9 (1.2)	2–3 × 5–12 repetitions 1–3 times per week 6 wk	ECC PT (60 deg/s) ECC PT (deg) BFlh architecture: FL, PA, VOL, and PCSA Stiffness Passive PT	NHE: +12% CG: no change	NHE: +11.9% CG: no change
Suarez-Arrones et al ⁶⁷	50 male professional soccer players NHE1: 16 NHE2: 17 CG: 17	18.8 (0.8)	2–3 × 5–10 repetitions 1–2 times per week 17 wk	ECC strength Sprint performance	NHE: 15.7% CG: 2.8%	NA

Abbreviations: ACSA, anatomical cross-sectional area; BFlh, biceps femoris long head; BFsh, biceps femoris short head; CG, control group; CON, concentric; ECC, eccentric; EMG, electromyography; FL, fascicle length; HE, hip extension; H:Q, hamstring:quadriceps; HC, hamstring curl; ISO, isometric; MT, muscle thickness; MVC, maximal voluntary contraction; NA, nonapplicable; NHE, Nordic hamstring exercise; PA, pennation angle; PCSA, physiological cross-sectional area; PT, peak torque; RSA, repeated sprint ability; SI, squat jump; ST, semitendinosus; VOL, volume.

Table 2 Risk of Bias of the Included Studies

Study	Adequate sequence generation	Allocation concealment	Blinding of outcome assessors	Description of losses and exclusions	Incomplete outcome data	Selective outcome reporting
Bourne et al ⁵⁷	Low risk	Unclear	Low risk	Unclear	Low risk	Low risk
Delahunt et al ⁵⁹	Low risk	Low risk	Low risk	Unclear	Low risk	Low risk
Delextrat et al ⁶⁰	Low risk	Unclear	Low risk	Low risk	Low risk	Low risk
Iga et al ⁶¹	Unclear	Unclear	Low risk	Unclear	Low risk	Low risk
Ishøi et al ⁶²	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Lovell et al ⁶³	Unclear	Unclear	Unclear	Low risk	Low risk	Low risk
Mendiguchia et al ⁶⁴	Unclear	Unclear	Low risk	Low risk	Low risk	Low risk
Mjølsnes et al ⁶⁵	Low risk	Unclear	Low risk	Low risk	Low risk	High risk
Ribeiro-Alvares et al ⁶⁶	Low risk	Unclear	High risk	Unclear	Low risk	Low risk
Salci et al ⁵⁵	Unclear	Low risk	Unclear	Low risk	Low risk	Low risk
Seymore et al ⁵⁶	Unclear	Unclear	Unclear	Unclear	Low risk	Low risk
Suarez-Arrones et al ⁶⁷	High risk	High risk	Unclear	Low risk	Low risk	Low risk

Figure 2 — Analysis of eccentric strength during isokinetic dynamometry. CG indicates control group; CI, confidence interval; NHE, Nordic hamstring exercise.

Figure 3 — Analysis of eccentric strength during Nordic hamstring exercise test. CG indicates control group; CI, confidence interval; NHE, Nordic hamstring exercise.

Figure 4 — Analysis of fascicle length. CG indicates control group; CI, confidence interval; NHE, Nordic hamstring exercise.

active lengthening muscle action to decelerate both the hip flexion and the knee extension.^{69,70} Therefore, it seems plausible that increasing eccentric strength might decrease the risk of sustaining an HSI. However, the literature is not definitive regarding the role of poor hamstring strength as a risk factor for HSI. For instance, Van Dyk et al⁷¹ concluded that poor hamstring strength is a weak risk factor for HSI after assessing 614 professional soccer players through isokinetic dynamometry at preseason and following them along the season. On the other hand, Timmins et al²⁹ and Lee et al³⁰ prospectively assessed the hamstring eccentric strength of professional soccer players during the NHE execution and isokinetic dynamometry, respectively; those studies found that injured players throughout the subsequent season were approximately 13% to 19% weaker than the uninjured players. Despite these conflicting findings, it seems reasonable to assume that muscle weakness can never be considered as normal, and should always be addressed properly, especially in athletic populations.

The current review evidenced that NHE-based training was associated with increase in knee flexors eccentric strength. It is important to highlight that NHE training generated significant increases on eccentric strength in all studies assessed by our review, regardless the type of evaluation performed. When tests were performed on the isokinetic dynamometer, strength gains ranged between 10% and 15%, while studies comprising tests on the NHE device found increases from 16% to 26%. The greater percentage strength gains reported on the NHE device is probably related to training specificity.⁷² As the NHE device mimics the exact movement performed during the training program, it is reasonable to assume that the gains would be higher when compared with the isokinetic dynamometry, which involves a totally different testing setting.

Studies included in this review assessed participants with different conditioning levels (from physically active university students⁶⁶ to professional soccer players⁶²). It is a factor that significantly influences the responses to any type of strength training, including the NHE. In addition, the training protocols varied among the studies regarding training period, weekly frequency, and total training volume. NHE training volume has been an issue of current interest as it remains a challenge for coaches and conditioning trainers to fit NHE training in an already busy schedule.⁷³ There seems to be a concern that the NHE added to the athletes' training routine will promote an overload of muscular work. Thus, the dose of NHE training that is sufficient to generate muscle adaptations without promoting excessive levels of fatigue remains uncertain.

Severo-Silveira et al⁷⁴ compared the effects of 2 NHE training programs (progressive workload, 236 repetitions along 8 wk; and constant workload, 138 repetitions along 8 wk) in Rugby players, and found that only the group trained with the greater training volume increased knee flexors eccentric strength. Nevertheless, performing NHE progressively during the season might not be suitable for the athletes' training routines. A possible solution for this issue could be performing high-volume training followed by a low-volume training. Presland et al⁷⁵ reported that 2 weeks of high-volume NHE training followed by 4 weeks of low-volume training (128 repetitions along 6 wk) generate similar adaptations when compared with 6 weeks of high-volume training (440 repetitions along 6 wk). Therefore, performing a high-volume training during the preseason and maintaining the gains with a low-volume training during the season might be more suitable for the teams' training routines. However, it is important to mention that there is no consensus in current literature regarding the minimal NHE training

volume required to promote significant increase in strength. For instance, all studies included in this review reported increase in hamstring eccentric strength, regardless of the periodization employed. This highlights the need for further studies regarding muscular adaptations promoted by the NHE training, especially to establish the optimal training volume for athletic populations.

Effects of NHE on Fascicle Length

In the last decades, the study of muscle architecture has been enabled by the introduction of 2D image ultrasound in this field.⁷⁶ This cost- and time-effective noninvasive and easily accessible tools have helped to expand the assessment of muscle thickness, pennation angle, and fascicle length of a range of muscles. Biceps femoris long head fascicle length is the most remarkable muscle architecture outcome related to HSI. Evidence suggests that previously injured biceps femoris long head muscles present significantly shorter fascicles than muscles without history of injury,⁷⁷ which might be one of the reasons why previously injured muscles have an increased chance of sustaining a new injury.³ Even more impressive are prospective findings that biceps femoris long head fascicles shorter than 10.56 cm at preseason increase more than 4 times the risk to HSI along the season in professional soccer players.²⁹ Therefore, biceps femoris long head fascicle length is considered the newest and a very promising risk factor for HSI in sports.

Fascicle length increase changes the force–velocity and force–length relationships, which directly impacts muscle function.⁷⁸ In theory, a muscle with longer fascicles contains a higher amount of in-series aligned sarcomeres, which would increase muscle contraction velocity⁷⁹ and also prevent the muscle from damage due to over-lengthening.³² On the other hand, a muscle with reduced fascicle length presents an increased muscle susceptibility to eccentrically induced microscopic muscle damage, which could facilitate a macroscopic damage.⁸⁰ Hence, exercises capable of increasing fascicle length might contribute to prevent HSI.

Our results support NHE training as an effective strategy to increase the biceps femoris long head fascicle length, as previously evidenced through isokinetic eccentric training of the hamstrings⁴⁰ and other muscle groups.^{42,81} All studies included in the current review that addressed fascicle length found that NHE training promoted significant increases in that outcome, independently of the training periodization or participants conditioning status. It is worth pointing out in this context that the only 2 studies^{74,75} to this date that have compared low and high volume of NHE training found that fascicle length is increased even with low-volume training programs. This information is relevant for clubs that have difficulties implementing high volumes of NHE training due to their tight schedule.

Interestingly, fascicle length enhancement seems to occur since the first month of NHE training.⁶⁶ Short-term responses might be useful for athletes who have short periods of preseason such as soccer players,^{43,44} given that they could start the competitive season with longer fascicles and less susceptibility to HSI. However, the quick fascicle length adaptation in response to NHE training has been evidenced only in a nonathletic population.⁶⁶ In well-trained athletes, a longer training period (8-wk NHE training program) seems to be necessary to increase the hamstring fascicle length.⁷⁴ Nonetheless, further investigations are needed to verify the short-term responses of fascicle length in this population.

According to the logistic regression performed by Timmins et al,²⁹ an increase in only 11% in biceps femoris long head fascicle length enables a decrease of approximately 21% in the probability of HSI. On the other hand, the same study demonstrated that increments of at least 50% in hamstring eccentric strength are required to achieve a similar decrease in the probability of injury,²⁹ which is a muscle strengthening hardly achieved in well-trained athletes. In the present review, the studies found increases in fascicle length from 12% to 22%, while the increases in eccentric strength ranged between 10% and 26%. Therefore, it seems reasonable to hypothesize that fascicle length changes might have a key role for the preventive effect of NHE. However, it is important to point out that fascicle length and eccentric strength only contribute to preventing HSI to some point. There are several other determinants suggested by prospective studies (eg, lumbopelvic stability, posterior chain flexibility, workload) that play a role in HSI and will be not modified through NHE training.

Strengths and Limitations

The current review is not without limitations. The main limitation of the present review is that we were not able to gather the totality of the studies in the quantitative analysis. Another limitation is the low to moderate methodological quality of the included studies. However, a strategy for a sensitive and comprehensive search to assure the location of all most recent studies in this field was held, further highlighting the need for additional investigations in that field. To the best of our knowledge, the current study is the first meta-analysis to exclusively analyze the role of NHE on specific hamstring injury risk factors (eccentric strength and fascicle length). Previous reviews^{82,83} have focused on HSI incidence, and even though we agree that this is the main variable in any injury prevention protocol, it is important to elucidate the mechanisms that underpin any positive results.

Conclusions

The present review evidenced that NHE is a valid strategy to enhance both knee flexors eccentric strength and fascicle length, 2 evidence-based risk factors for HSI. Our findings elucidated 2 of the main mechanisms that explain, at least in part, the preventive effect of NHE against HSI, and reinforce the adoption of this exercise during both training and rehabilitation programs. Nevertheless, further research is needed to verify the best NHE training protocol to modify eccentric strength and fascicle length without impairing athletes' performance and increasing risk of HSI.

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