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The Effects of Eccentric Training on Biceps Femoris Architecture and Strength: A Systematic Review With Meta-Analysis

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Objective: To determine the effects of an eccentric hamstrings strength-training program, performed for at least 4 weeks by healthy adults, on muscle architecture and eccentric strength.

Data Sources: A systematic search was performed up to October 2018 in the following electronic databases: PubMed, PEDro, CINAHL and SPORTDiscus. Combinations of the following search terms were used: *eccentric strength training*, *eccentric loading*, *nordic hamstring*, *hamstring strength*, *fascicle length*, *pennation angle*, *muscle thickness*, *muscle architecture*, *biceps femoris long head*, *biceps femoris*, and *hamstring muscles*.

Study Selection: Included articles were randomized controlled trials that allowed comparisons between isolated eccentric strength training of the biceps femoris muscle and other programs.

Data Extraction: Data from the included studies were extracted by 2 independent reviewers. These data included the study design, participant characteristics, inclusion and exclusion criteria of clinical studies, exercise and intervention characteristics, outcome measures, and the main results of the study. When meta-analysis was possible, we performed quantitative analysis. Ten randomized controlled trials were included.

Data Synthesis: Limited to moderate evidence indicated that eccentric strength training was associated with an increase in fascicle length (mean difference [MD] = 1.97; 95% confidence interval [CI] = 1.48, 2.46), an increase in muscle thickness (MD = 0.10; 95% CI = 0.06, 0.13), and a decrease in pennation angle (MD = 2.36; 95% CI = 1.61, 3.11). Conflicted to moderate evidence indicated that eccentric hamstrings strength was increased after eccentric strength training compared with concentric strength training (standardized mean difference [SMD] = 1.06; 95% CI = 0.26, 1.86), usual level of activity (SMD = 2.72; 95% CI = 1.68, 3.77), and static stretching (SMD = 0.39; 95% CI = –0.97, 1.75).

Conclusions: In healthy adults, an eccentric strength-training program produced architectural adaptations on the long head of the biceps femoris muscle and increased eccentric hamstrings strength.

Key Words: eccentric strength training, Nordic hamstrings, fascicle length, muscle architecture, eccentric hamstrings strength

Key Points

- In healthy adults, eccentric strength training was associated with architectural adaptations on the long head of the biceps femoris muscle and an increase in eccentric hamstrings strength.
- The effectiveness of eccentric strength training in preventing hamstrings strain injury may be mediated by the capacity to achieve higher forces and a greater capacity to support stretch during eccentric muscle actions.
- Further studies are needed to confirm these findings, determine guidelines for exercise selection, and standardize training methods for adoption in clinical practice.

Hamstrings strain injury (HSI) is one of the most common injuries in soccer, Australian football, rugby, and track and field sports, accounting for more than 12% of all lower extremity sports injuries,[1–4] and upward of 80% of these injuries involve the long head of the biceps femoris muscle (LHBF).[5–7] The HSI occurs either from extreme joint positions involving hip flexion and knee extension or during the terminal swing phase of high-speed running, when a muscle is eccentrically overstretched.[8–10] It is characterized by persistent symptoms and a high risk for recurrence, which result in lost participation time for athletes and reduced conditioning status and sport performances.[3,11,12] These data highlight the need to target and improve HSI prevention.

Whereas no researchers, to our knowledge, have found conclusive evidence for preventing HSI using flexibility[11,13,14] or core-stability training,[14] chronic eccentric strength-training (EST) programs have been shown to reduce hamstrings injuries in several field sports, including amateur and professional soccer,[13,15–18] professional rugby,[19] and professional baseball.[20] However, the mechanism behind this reduction remains unclear. Additionally, despite an increased focus on prophylactic programs for HSI, no researchers have provided guidelines for selecting exercises.[21,22]

Although the causes of hamstrings injury are multifactorial,[3] prevention programs have focused on modifiable HSI risk factors, such as eccentric hamstrings weak-

Table 1. Search Strategy to Identify Relevant Studies in PubMed

	Search Terms	No. of Articles Found in PubMed
1	Eccentric strength training	42
2	Eccentric loading	217
3	Nordic hamstring	71
4	(1) OR (2) OR (3)	326
5	Fascicle length	540
6	Pennation angle	472
7	Muscle thickness	1826
8	Muscle architecture	716
9	Biceps femoris long head	103
10	Biceps femoris	3069
11	Hamstring muscles	1085
12	Hamstring strength	287
13	(5) OR (6) OR (7) OR (8) OR (9) OR (10) OR (11) OR (12)	6979
14	Healthy	742 748
15	Adult	5 221 793
16	(14) OR (15)	5 587 255
17	(4) AND (13) AND (16)	45

ness[7,23,24] and, more recently, muscle architecture.[24] Timmins et al[24] reported that soccer players with shorter LHBF fascicles were at greater risk of HSI than players with longer fascicles. In a retrospective study, Malliaropoulos et al[22] suggested that lesions in the LHBF seem to modify the architecture, reducing the fascicle length and increasing the pennation angle when compared with uninjured contralateral limbs. Moreover, muscle strength and architectural characteristics are adaptable and can be altered by several stimuli, including eccentric strength training (EST).[15,16,25,26] These variations have also been shown to modify muscle function.[27] Therefore, an improved understanding of the adaptations that EST provides could lead to more efficient methods for optimizing prevention. Therefore, the purpose of our systematic review and meta-analysis of randomized controlled trials was to provide an evidence-based framework for eccentric hamstrings training to prevent HSI, synthesizing the effects of eccentric hamstrings strength training on LHBF architecture and eccentric hamstrings strength, in healthy adults. We aimed to discuss (1) the effect and the role these architectural and strength alterations may have regarding the cause of an HSI, (2) clinical guidelines for eccentric hamstrings exercise selection, and (3) training modalities.

METHODS

Search Strategy

This systematic review and meta-analysis followed the guidelines provided in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (PROSPERO registration number: CRD42018109572).[28] A systematic search was performed to identify relevant studies through October 2018 in the following electronic databases: PubMed, PEDro, CINAHL and SPORTDiscus. Combinations of the following search terms were used: *eccentric strength training*, *eccentric loading*, *nordic hamstring*, *hamstring strength*, *fascicle length*, *pennation angle*, *muscle thickness*, *muscle architecture*, *biceps femoris long head*, *biceps femoris*, and *hamstring muscles* (Table 1). Reference lists and cited articles in all included papers were also screened.

Study Selection

All studies were screened and assessed independently by 2 researchers (R.G. and L.G.) for our inclusion and exclusion criteria. Studies were considered relevant if (1) the participants were healthy, (2) the participants were adults (only adults between 18 and 50 years of age were included), (3) the study design was a randomized controlled trial and allowed comparisons between isolated EST of the biceps femoris muscle and other programs (eg, concentric strength training, stretching programs, regular activities, isometric strength training, or plyometric strength training), (4) the program intervention in both comparison groups lasted at least 4 weeks, and (5) pre-evaluations and postevaluations included hamstrings eccentric strength assessed using an isokinetic dynamometer or 1-repetition maximum and biceps femoral architecture assessed using magnetic resonance imaging or ultrasound. Muscle architecture measures were fascicle length (the length of the fascicles running between the aponeuroses or tendons), muscle thickness (the distance between the superficial and deep or intermediate aponeuroses), and pennation angle (the angle formed by the fascicles and deep aponeurosis).[29,30] Studies were excluded if the (1) article was not written in English, (2) experiment was not performed on humans, or (3) participants had systemic diseases, a history of hamstrings injury, or a musculoskeletal disorder.

Data Extraction, Analysis, and Synthesis

Data from the included studies were extracted by 2 independent reviewers (R.G. and L.G.) using comparative tables. If any disagreements arose, a third reviewer (J.V.C.) was consulted. These data consisted of the study design (authors, date), participant characteristics (sample size, age, activity level), inclusion and exclusion criteria of the clinical studies, exercise and intervention characteristics,[31,32] outcome measures assessed at baseline and within 7 days of the final training session, and main results of the study. If data were missing, information was requested from the authors.

When meta-analysis was possible, we performed quantitative analysis using Review Manager software (version 5.3; The Nordic Cochrane Centre, Copenhagen, Denmark). The differences in pre-intervention and postintervention mean and standard deviation (SD) values were used to calculate the standardized mean difference (SMD). Consistent with Borenstein et al,[33] in case of incomplete data, we calculated missing change score SDs (SD_{change}) from SD values at baseline (SD_{pre}) and postintervention (SD_{post}) using the following formula: $\sqrt{\left[\left(SD_{pre}{}^2/N_{pre}\right)+\left(SD_{post}{}^2/N_{post}\right)\right]}$, where N was the number of participants at baseline (N_{pre}) and postintervention (N_{post}).

Forest plots were created to present the SMD with 95% confidence intervals (CIs) of the muscle architecture and muscular strength, and a random-effects model was applied. The analysis of statistical heterogeneity was verified using the I^2 test, which was interpreted as *low* (<30%), *moderate* (30%–60%), or *high* (>60%), and the χ^2 test with the α level set at .05. If the data were insufficient for a meta-analysis, a descriptive analysis was performed.[34]

Methodologic Quality Assessment

Methodologic quality was assessed for each study using the suggested risk-of-bias criteria for Effective Practice and Organisation of Care reviews.[35] The risk of bias was examined using 9 criteria that were rated as *high*, *low*, or *unclear*: random sequence generation, allocation concealment, similar baseline outcome measurements, similar baseline characteristics, incomplete outcome data, knowledge of the allocated interventions was adequately prevented during the study, protection against contamination, selective outcome reporting, and other risk of bias. This scale also enabled us to evaluate the presence of other biases. Two reviewers (R.G. and L.G.) independently rated each study, and a third reviewer (J.V.C.) was consulted in case of disagreement. Additionally, to draw conclusions about the overall risk of bias within trials, reviewers rated studies using predetermined criteria.[36] We rated the risk as *low* if all items had a low risk of bias, *unclear* if all items had an unclear risk of bias, and *high* if ≥1 item had a high risk of bias.

Level of Evidence

The level of evidence supporting the effects of EST on fascicle length, pennation angle, muscle thickness, and eccentric hamstrings strength in comparison with control groups was established using predetermined criteria.[37] *Very strong evidence* was based on results derived from a minimum of 2 studies rated as having a low risk of bias and a low level of heterogeneity. *Strong evidence* was based on results derived from a minimum of 2 studies rated as having a low risk of bias and a moderate or high level of heterogeneity or from multiple studies rated as having an unclear risk of bias and a low level of heterogeneity. *Moderate evidence* described results from multiple studies rated as having an unclear risk of bias and a moderate or high level of heterogeneity, from multiple studies rated as having a high risk of bias and a low level of heterogeneity, or from 1 study rated as having a low risk of bias. *Limited evidence* portrayed results from multiple studies rated as having a high risk of bias and a moderate or high level of heterogeneity or from 1 study rated as having an unclear risk of bias. *Very limited evidence* was based on results from 1 study rated as having a high risk of bias. *Conflicting evidence* described pooled results, which were not different, derived from multiple studies, some of which individually were different, regardless of quality, which was statistically heterogeneous ($P < .05$).

RESULTS

Results of Study Selection

Using the search strategy, we identified 251 studies. After duplicates were removed, 179 potentially relevant articles were examined by title and abstract. Of these, 156 were excluded. An additional 11 publications were identified by searching the reference lists of the remaining publications. Of the 34 articles retrieved for full-text review, 24 did not meet the inclusion criteria. Therefore, we included 10 studies in this systematic review.[38–47] Figure 1 shows the selection process.

Methodologic Quality Assessment of the Included Studies

The methodologic quality assessment is provided in Figure 2 and Table 2. Five studies[38–40,45,47] reported the assessors were blinded. Only 4 studies demonstrated no differences in outcome measurements[42,44,45,47] or population characteristics[38,40,44,47] across study groups before the intervention. Moreover, 7 studies[38,40–44,47] did not report allocation concealment. Based on how the previous criteria were fulfilled, we rated the overall risk of bias within trials. Four studies[38,39,41,47] were rated as having an unclear risk of bias, and 6 studies[40,42–46] were rated as having a high risk of bias.

Participants

In total, 346 participants were involved in the studies. The number of participants ranged from 18[40,42] to 119.[45] The average age of participants ranged from 18.3[46] to 29.6[43] years. Some participants were professional,[40] semiprofessional,[45] or amateur[42] soccer players. Other participants were recreationally active people,[38,39,44,46,47] and activity levels were not specified in 2 studies.[41,43] The participants' characteristics are shown in Table 3.

Inclusion and Exclusion Criteria of Clinical Studies

Only male participants were included in 6 studies,[38–40,42,45,47] and volunteers were required to be ≥18 years of age in 3 studies.[39,45,46] Nine studies[38,39,41–47] excluded participants presenting with a history of lower limb injury or HSI within the previous 6 months. Four studies[39,41,43,44] excluded participants undergoing lower limb strength training, and 2 studies[41,44] excluded individuals who used performance-enhancing drugs. In 1 study,[46] volunteers with a body mass index ≥30 kg/m^2 were excluded.

Intervention Description and Protocol

Most studies[38–40,42,44–46] used the Nordic hamstrings exercise (NHE). Two studies[41,43] used eccentric hamstrings curls for intervention training, 1 study[38] used a hip-extension exercise, and 1 study[47] used an eccentric knee-flexion exercise. In 6 intervention programs, participants needed a partner to perform the exercise,[39,40,42,44–46] and 4 programs required equipment.[38,41,43,47] Intervention programs were most often performed after a warmup[40–47]; only 1 intervention group performed the intervention program after soccer training.[42] Most studies[38,39,42–45,47] were supervised by authors or trained staff, whereas the type of supervision was not specified in 3 studies.[40,41,46] Control groups continued with their usual level of physical activity[38–40,44] or performed static stretching,[45,46] concentric training,[41,43,47] or core-stability exercises.[42] The duration of the training ranged from 4 weeks[40,44] to 10 months,[45] and each session was conducted at least once a week[39,40,46] and up to 3 times a week.[39,40,43,45–47] Load magnitude varied from body weight[38–40,42,44–46] to maximum-intensity load.[38,41,43,47] The requested repetitions ranged from 1[43] to 12[39,42,45,46] for set numbers ranging from 2[38–42,45,46] to 6.[38,47] The exercise interventions are described in Table 4.

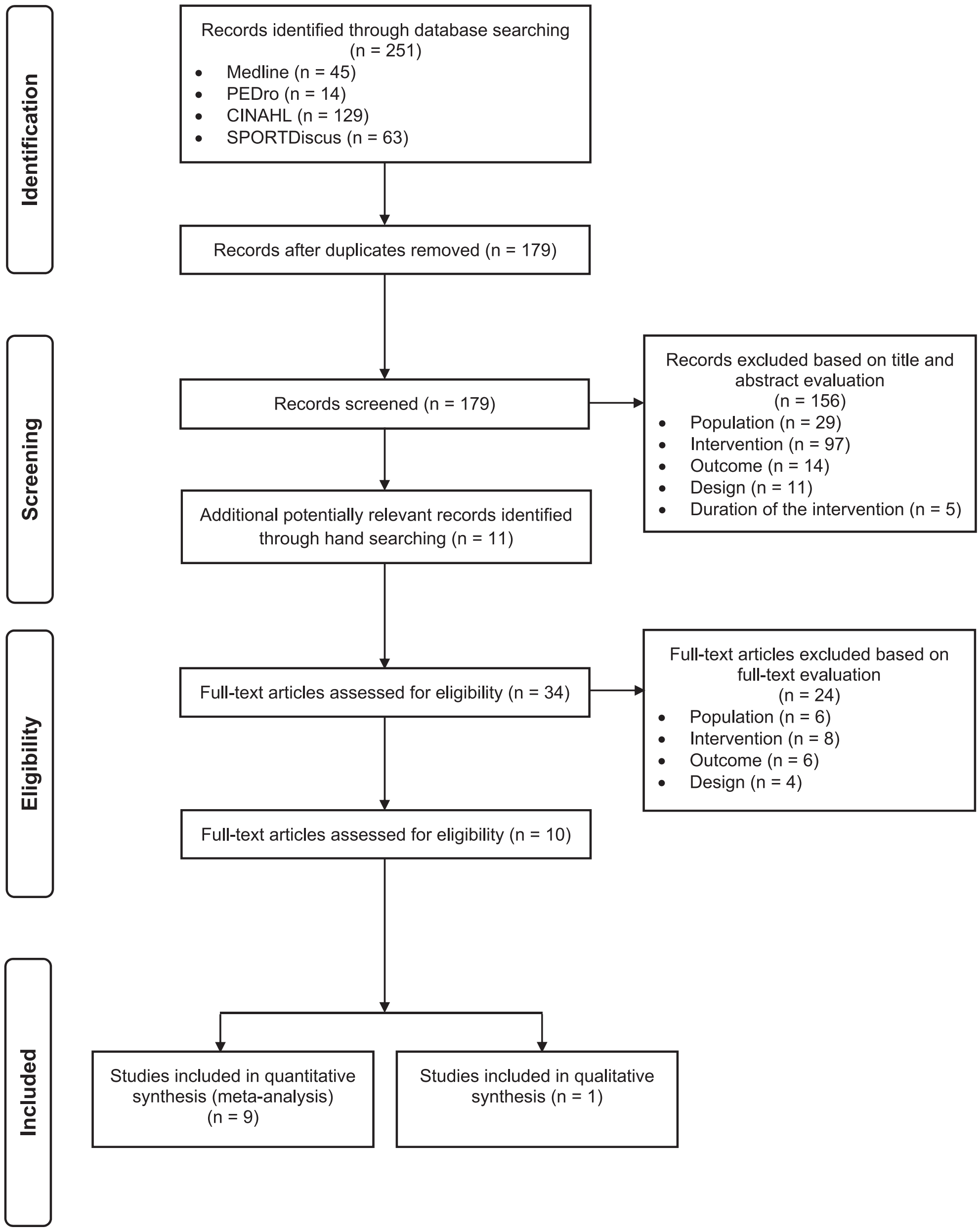


Figure 1. Flow chart of the study-selection process.

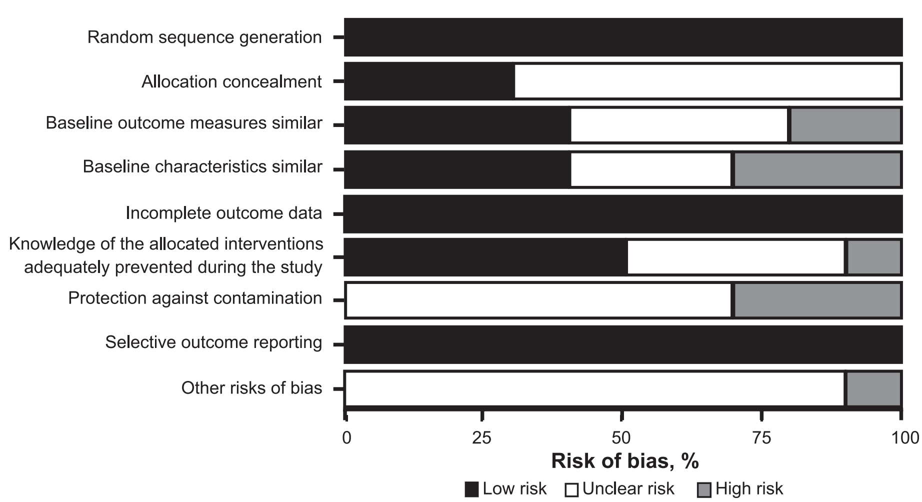


Figure 2. Authors' judgments about each risk-of-bias item[36] presented as percentages across all included studies.

Table 2. Risk-of-Bias Summary: Review of the Authors' Judgements About Included Studies' Risk of Bias Using the Suggested Criteria for Effective Practice and Organization of Care Reviews[35]

Item	Study (Year)									
	Bourne et al[38] (2017)	Delahunt et al[39] (2016)	Iga et al[40] (2012)	Kaminski et al[41] (1998)	Lovell et al[42] (2018)	Potier et al[43] (2009)	Ribeiro-Alvarez[44] (2018)	Sebelien et al[45] (2014)	Seymore et al[46] (2017)	Timmins et al[47] (2016)
Random sequence generation	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Allocation concealment	Unclear	Low	Unclear	Unclear	Unclear	Unclear	Unclear	Low	Low	Unclear
Similar baseline outcome measurements	Unclear	Unclear	Unclear	Unclear	Low	High	Low	Low	High	Low
Similar baseline characteristics	Low	Unclear	Low	Unclear	High	High	Low	High	Unclear	Low
Incomplete outcome data	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Knowledge of the allocated interventions adequately prevented during the study	Low	Low	Low	Unclear	Unclear	Unclear	High	Low	Unclear	Low
Protection against contamination	Unclear	Unclear	High	Unclear	High	Unclear	Unclear	High	Unclear	Unclear
Selective outcome reporting	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Other risks of bias	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	Unclear	High	Unclear	Unclear

Outcome Measures

Eccentric hamstrings strength was assessed at baseline and within 7 days of the final training session in all studies.[38–47] An isokinetic dynamometer was used to evaluate eccentric hamstrings peak torque (Nm) at 30,[42] 60,[40,44,45,47] 120,[39,40] 180,[47] and 240°/s[40]; eccentric hamstrings peak torque relative to body mass (Nm/kg) at 60,[41,46] 120,[39] and 180°/s[41]; and the eccentric hamstrings peak torque-to-concentric quadriceps peak torque functional ratio.[44,45] The hamstrings leg-curl machine was chosen to assess the 1-repetition maximum eccentric hamstrings strength (kg).[43] Three repetitions of the NHE were used to evaluate the maximum eccentric knee-flexor strength (N),[38] and a 45° hip-extension exercise machine was used to determine the 3 repetitions of maximum eccentric hamstrings strength (kg).[38]

Architectural modifications were assessed at baseline and within 7 days of the final training session test in 6 studies.[38,42,43,44,46,47] Ultrasound images were chosen to assess the fascicle length (cm),[38,42,43,44,46,47] muscle thickness (cm),[42,44,47] and pennation angle (°)[42–44,46,47] of the biceps femoris.

Study Results

Effect of Eccentric Strength Training on Fascicle Length. Five studies[38,43,44,46,47] involving 9 comparisons evaluated the effects of EST on fascicle length. Moderate evidence indicated that EST more effectively increased fascicle length (mean difference [MD] = 1.97; 95% CI = 1.48, 2.46; Figure 3). Given the missing data and insufficient information to calculate SDs with matching 95% CIs, the data from Lovell et al[42] were not pooled. When compared with the core-stability group, the authors reported an increase in fascicle length in the eccentric group when NHE was administered before field-training sessions and no difference in fascicle length in the eccentric group when NHE was administered after field-training sessions.

Effect of Eccentric Strength Training on Muscle Thickness. Two studies[44,47] involving 5 comparisons

Table 3. Participants' Characteristics

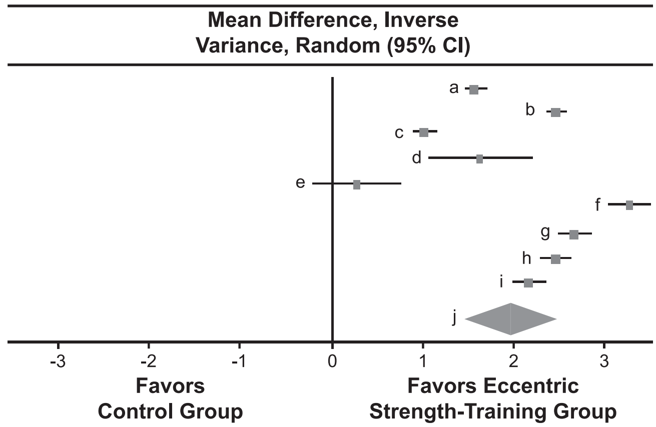
Study	Group	No. of Participants	Age, y, Mean ± SD or Range	Activity Level
Bourne et al[38] (2017)	Control	10	21.3 ± 3.7	Recreationally active men
	Intervention (hip-extension exercise)	10	23.1 ± 4.1	
	Intervention (Nordic hamstrings exercise)	10	21.6 ± 3.2	
Delahunt et al[39] (2016)	Control	14	22 ± 1.38	Recreationally active men
	Intervention	15		
Iga et al[40] (2012)	Control	8	22.3 ± 3.9	Professional male soccer players
	Intervention	10	23.4 ± 3.3	
Kaminski et al[41] (1998)	Control	9	23.3 ± 3.5	Not mentioned
	Intervention	9	22.9 ± 3.8	
Lovell et al[42] (2018)	Control	12	23.6 ± 4.7	Amateur male soccer players
	Intervention (before training)	14		
	Intervention (after training)	16		
Potier et al[43] (2009)	Control	11	29.6 ± 1.2	Not mentioned
	Intervention	11	27 ± 0.8	
Ribero-Alvares et al[44] (2018)	Control	10	26.0 ± 2.7	Moderately physically active people
	Intervention	10	23.7 ± 3.3	
Sebelien et al[45] (2014)	Control	59	18–29	Semi-professional male soccer players
	Intervention	60	20–36	
Seymore et al[46] (2017)	Control	10	19.9 ± 1.2	Recreationally active people
	Intervention	10	18.3 ± 0.5	
Timmins et al[47] (2016)	Control	14	23.4 ± 5.1	Recreationally active men
	Intervention	14	21.2 ± 2.7	

Table 4. Exercise Interventions

Study (Year)	Type of Exercise	Materials	Progression	Warmup	Procedure
Bourne et al[38] (2017)	NHE	Padded board, ankle braces, circular weight plate(s) (2.5 kg)	+2.5 kg load for 10 wk	Not specified	2–6 sets × 5–10 repetitions, 3-min rest between sets, 2x/wk
	Hip-extension exercise	45° Hip-extension machine,[a] ankle pad, circular weight plate(s) (2.5 kg)	Wk 1: 60–70% 1RM// 70–80% 1RM Wk 2–10: Maximal intensity	Not specified	2–6 sets × 5–10 repetitions, 3-min rest between sets, 2x/wk
Delahunt et al[39] (2016)	NHE	1 Partner	Body weight for 6 wk	No specified	2–3 sets × 5–12 repetitions, 2-min rest between sets, 1–3x/wk
Iga et al[40] (2012)	NHE	1 Partner	Body weight for 4 wk	Training conducted at the beginning of the practice session after a dynamic warmup	2–3 sets × 5–8 repetitions, 1–3x/ wk
Kaminski et al[41] (1998)	Hamstrings curls	Isotonic hamstrings leg-curl machine	100% 1RM with increase of 5.44 kg/wk for 6 wk	Training conducted after 3 min of stationary bicycling, lower extremity flexibility program, and 1 set × 8 repetitions of eccentric hamstrings curls (50% RM)	2 sets × 8 repetitions, 1-min rest between sets, 2x/wk
Lovell et al[42] (2018)	NHE	1 Partner	Body weight for 12 wk	Training conducted at the beginning of the practice session after a dynamic warmup	2–4 sets × 5–12 repetitions, 2x/wk
Potier et al[43] (2009)	Hamstrings curls	Isotonic hamstrings leg-curl machine	100% 1RM for 8 wk	Training conducted after 3 min of exercise bicycling and 1 set × 8 repetitions of eccentric hamstrings curls (50% RM)	3 sets × 1–8 repetitions, 3x/wk
Ribero-Alvares et al[44] (2018)	NHE	1 Partner	Body weight for 4 wk	Training conducted after a warmup of 10 submaximal concentric knee extension-flexion repetitions (120°/s)	3 sets × 6–10 repetitions, 1-min rest between sets, 2x/wk
Sebelien et al[45] (2014)	NHE	1 Partner	Body weight for 10 mo	Training administered after a general warmup (jogging and light sprinting) and stretching	2–3 sets × 5–12 repetitions, 2–3x/ wk
Seymore et al[46] (2017)	NHE	1 Partner	Body weight for 6 wk	Training administered after 5 min on a cycle ergometer and static hamstrings stretching	2–3 sets × 5–12 repetitions, 1–3x/wk
Timmins et al[47] (2016)	Eccentric knee flexion	Isokinetic dynamometer	Maximal intensity for 6 wk	Training conducted after 2 sets of 3 eccentric warmup efforts at 60°/s	4–6 sets × 6–8 repetitions, 30-s rest between sets, 2–3x/wk

Abbreviations: 1RM, 1-repetition maximum; NHE, Nordic hamstrings exercise; RM, repetition maximum.

[a] BodySolid, Inc, Forest Park, IL.



Study Name	Subgroup Within Study	Control Group Mean ± SD	Control Group Total, No.	Eccentric Strength-Training Group Mean ± SD	Eccentric Strength-Training Group Total, No.	Weight, %	Mean Difference Inverse Variance, Random (95% CI)
a. Bourne et al[38] (2017)	Ecc HEE vs ULA	−0.25 ± 0.14	10	1.33 ± 0.12	10	11.4	1.58 (1.47, 1.69)
b. Bourne et al[38] (2017)	Ecc NHE vs ULA	−0.25 ± 0.14	10	2.22 ± 0.11	10	11.4	2.47 (2.36, 2.58)
c. Potier et al[43] (2009)	Ecc vs Con	0.95 ± 0.15	11	1.98 ± 0.14	11	11.4	1.03 (0.91, 1.15)
d. Ribeiro-Alvares et al[44] (2018)	Ecc vs NA	0.19 ± 0.85	10	1.82 ± 0.31	10	10.0	1.63 (1.07, 2.19)
e. Seymore et al[46] (2017)	Ecc vs SS group	−0.18 ± 0.37	10	0.11 ± 0.67	10	10.4	0.29 (−0.18, 0.76)
f. Timmins et al[47] (2016)	0% MVIC Ecc vs Con	−1.38 ± 0.32	14	1.89 ± 0.27	14	11.2	3.27 (3.05, 3.49)
g. Timmins et al[47] (2016)	25% MVIC Ecc vs Con	−1.06 ± 0.27	14	1.61 ± 0.21	14	11.3	2.67 (2.49, 2.85)
h. Timmins et al[47] (2016)	50% MVIC Ecc vs Con	−0.81 ± 0.23	14	1.65 ± 0.21	14	11.4	2.46 (2.30, 2.62)
i. Timmins et al[47] (2016)	75% MVIC Ecc vs Con	−0.58 ± 0.23	14	1.59 ± 0.23	14	11.3	2.17 (2.00, 2.34)
j. Total			107		107	100.0	1.97 (1.48, 2.46)

Heterogeneity: $T^2 = 0.55$, $\chi^2_8 = 635.84$, $P < .001$, $I^2 = 99\%$

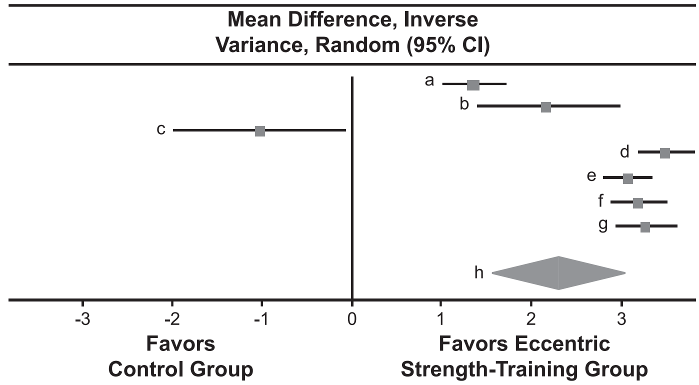
Test for overall effect: $Z = 7.86$; $P < .001$

Figure 3. Forest plot of the difference in fascicle length between eccentric strength-training and control groups. Abbreviations: CI, confidence interval; Con, concentric; Ecc, eccentric; HEE, hip-extension exercise; MVIC, maximal voluntary isometric contraction; NA, no activity; NHE, Nordic hamstrings exercise; SS, static stretching; ULA, usual level of activity.

addressed the effects of EST on muscle thickness. Limited evidence showed that EST more effectively increased muscle thickness (MD = 0.10; 95% CI = 0.06, 0.13; Figure 5). Lovell et al[42] did not provide sufficient information for calculating SDs with matching 95% CIs. However, compared with the core-stability group, they described an increase in muscle thickness in the eccentric group when the NHE was administered after field-training sessions and no difference when the NHE was administered before field-training sessions.

Effect of Eccentric Strength Training on Pennation Angle. Four studies[43,44,46,47] involving 7 comparisons examined the effects of EST on the pennation angle. Limited evidence demonstrated that EST more effectively decreased the pennation angle (MD = 2.36; 95% CI = 1.61, 3.11; Figure 4). The data from Lovell et al[42] were not pooled. When compared with the core-stability group, pennation angle increased in the eccentric group when the NHE was administered after field-training sessions but no difference occurred when the NHE was administered before field-training sessions.

Effect of Eccentric Strength Training on Eccentric Hamstring Strength. Three studies[41,43,47] with 5 outcome measures compared the effects of EST with concentric strength training on eccentric hamstrings strength. Moderate evidence indicated that EST more effectively increased eccentric hamstrings strength (SMD = 1.06; 95% CI = 0.26, 1.86). Similarly, 4 studies[38–40,44] with 14 outcome measures compared the effects of EST with the usual level of activity on eccentric hamstrings strength. Moderate evidence revealed that EST more effectively increased eccentric hamstrings strength (SMD = 2.72; 95% CI = 1.68, 3.77). Two studies[45,46] with 3 outcome measures compared the effects of EST with static stretching on eccentric hamstrings strength. Conflicting evidence demonstrated no superiority of increasing eccentric hamstrings strength (SMD = 0.39; 95% CI = –0.97, 1.75). Figures 6 through 8 display forest plots of the differences in eccentric hamstrings strength between the EST and control groups.



Study Name	Subgroup Within Study	Control Group		Eccentric Strength-Training Group		Weight, %	Mean Difference Inverse Variance, Random (95% CI)
		Mean ± SD	Total, No.	Mean ± SD	Total, No.		
a. Potier et al[43] (2009)	Ecc vs Con	−0.9 ± 0.28	11	0.5 ± 0.51	11	14.9	1.40 (1.06,1.74)
b. Ribeiro-Alvares et al[44] (2018)	Ecc vs NA	0.13 ± 0.92	10	2.36 ± 0.88	10	13.1	2.23 (1.44, 3.02)
c. Seymore et al[46] (2017)	Ecc vs SS	−0.3 ± 0.82	10	−1.3 ± 1.32	10	12.2	−1.00 (−1.96, −0.04)
d. Timmins et al[47] (2016)	0% MVIC Ecc vs Con	−2.53 ± 0.38	14	1.02 ± 0.45	14	14.9	3.55 (3.24, 3.86)
e. Timmins et al[47] (2016)	25% MVIC Ecc vs Con	−2.21 ± 0.37	14	0.92 ± 0.36	14	15.0	3.13 (2.86, 3.40)
f. Timmins et al[47] (2016)	50% MVIC Ecc vs Con	−1.98 ± 0.4	14	1.27 ± 0.44	14	14.9	3.25 (2.94, 3.56)
g. Timmins et al[47] (2016)	75% MVIC Ecc vs Con	−1.64 ± 0.44	14	1.49 ± 0.44	14	14.9	3.33 (3.00, 3.66)
h. Total			87		87	100.0	2.36 (1.61, 3.11)

Heterogeneity: $T^2 = 0.96$, $\chi^2_6 = 170.23$, $P < .001$, $I^2 = 96\%$

Test for overall effect: $Z = 6.17$; $P < .001$

Figure 4. Forest plot of the difference in pennation angle between eccentric strength-training and control groups. Abbreviations: CI, confidence interval; Con, concentric; Ecc, eccentric; MVIC, maximal voluntary isometric contraction; NA, no activity; SS, static stretching.

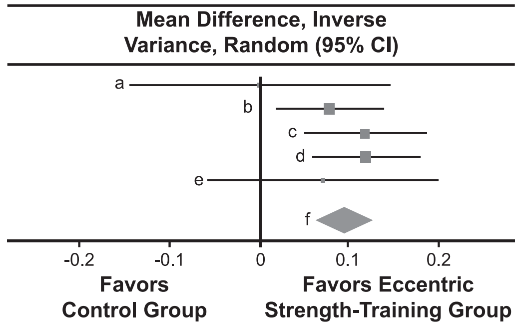
Given the missing data, the Lovell et al[42] data were not pooled, but the investigators reported increased eccentric hamstrings peak torque in the eccentric groups when the NHE was administered before field-training sessions (11.9%; 90% CI = 3.6%, 20.9%) and after field-training sessions (11.6%; 90% CI = 2.6%, 21.5%) when compared with the core-stability group.

DISCUSSION

The aim of our systematic review and meta-analysis was to determine the effect of an EST performed by healthy adults on LHBF architecture and eccentric hamstrings strength versus comparison programs. The results provided evidence that EST affects the HSI modifiable risk factors, resulting in muscle architecture adaptations and improved eccentric hamstrings strength.

Researchers[24,48–50] found that higher eccentric hamstrings strength was associated with reduced HSI. The mechanisms for these improvements after eccentric training include a combination of neural and architectural factors.[29,51–54] Some evidence has indicated that changes in eccentric strength are achieved via increased muscle excitability,[55,56] which is influenced by the size (ie, the type of muscle fibers) and the number of recruited motor units, motor-unit discharge rate, and synchrony.[52,57] Furthermore, muscle architecture governed by mechanical stress is a key factor in the development of skeletal muscle force.[29,58] Adaptations in muscle architecture are related to fascicle lengthening, pennation angle of the biceps femoris muscle, and muscle thickness. Fascicle lengthening is thought to result in a greater number of in-series sarcomeres[59] and reduce the heterogeneous arrangement of these sarcomeres.[60] Increased fascicle length enhances the capacity to support stretch and reduce sarcomere strain when the hamstrings are actively lengthened during intermittent high-intensity exercise.[60,61] This capacity is associated with decreased microscopic damage and may protect against HSI.[24,62] Our results provide moderate evidence that EST effectively increases the fascicle length of the biceps femoris muscle when compared with control individuals. Similar results have been reported in 2 nonrandomized controlled trials[63,64] and 1 prospective cohort study.[65] Moreover, researchers using programs including eccentric-only exercise observed increases from 7.44% to 20% in the fascicle length of the semitendinosus,[65] quadriceps femoris,[26,66–68] and medial gastrocnemius[69] muscles across a 7- to 14-week training period.

Although muscle thickness is not recognized as an HSI risk factor, it is a strong determinant of muscle strength.[29] Increases in muscle thickness and pennation angle are

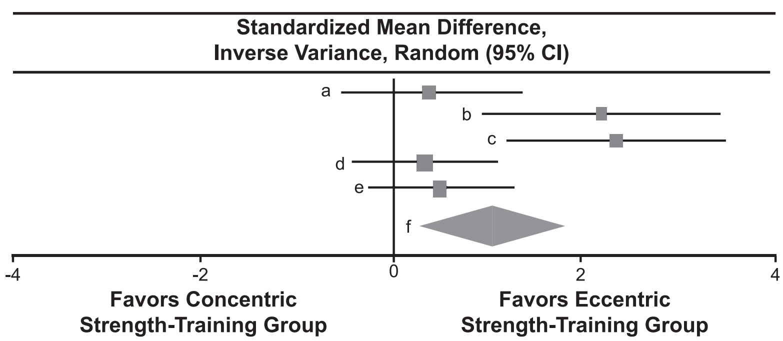


		Control Group		Eccentric Strength-Training Group			
Study Name	Subgroup Within Study	Mean ± SD	Total, No.	Mean ± SD	Total, No.	Weight, %	Mean Difference Inverse Variance, Random (95% CI)
a. Ribeiro-Alvares et al[44] (2018)	Ecc vs NA	0.02 ± 0.18	10	0.02 ± 0.15	10	5.3	0.00 (−0.15, 0.15)
b. Timmins et al[47] (2016)	0% MVIC Ecc vs Con	0.14 ± 0.08	14	0.22 ± 0.08	14	31.6	0.08 (0.02, 0.14)
c. Timmins et al[47] (2016)	25% MVIC Ecc vs Con	0.09 ± 0.08	14	0.21 ± 0.1	14	24.7	0.12 (0.05, 0.19)
d. Timmins et al[47] (2016)	50% MVIC Ecc vs Con	0.09 ± 0.08	14	0.21 ± 0.08	14	31.6	0.12 (0.06, 0.18)
e. Timmins et al[47] (2016)	75% MVIC Ecc vs Con	0.11 ± 0.08	14	0.18 ± 0.23	14	6.8	0.07 (−0.06, 0.20)
f. Total			66		66	100.0	0.10 (0.06, 0.13)

Heterogeneity: $T^2 = 0.00$, $\chi^2_4 = 3.23$, $P = .52$, $I^2 = 0\%$

Test for overall effect: $Z = 5.74$; $P < .001$

Figure 5. Forest plot of the difference in muscle thickness between eccentric strength-training and control groups. Abbreviations: CI, confidence interval; Con, concentric; Ecc, eccentric; MVIC, maximal voluntary isometric contraction; NA, no activity.

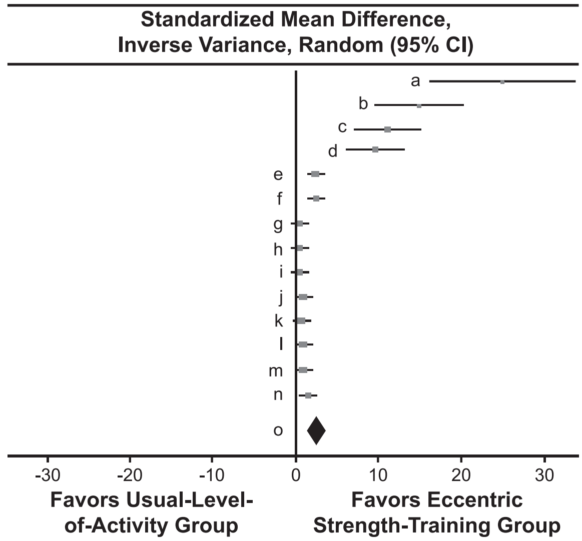


		Concentric Strength-Training Group		Eccentric Strength-Training Group			
Study Name	Subgroup Within Study	Mean ± SD	Total, No.	Mean ± SD	Total, No.	Weight, %	Standardized Mean Difference Inverse Variance, Random (95% CI)
a. Kaminski et al[41] (1998)	180°/s Ecc Ham PT, Nm/kg	0.16 ± 0.1	9	0.2 ± 0.09	9	20.2	0.40 (−0.54, 1.34)
b. Kaminski et al[41] (1998)	60°/s Ecc Ham PT, Nm/kg	0.03 ± 0.1	9	0.26 ± 0.1	9	16.9	2.19 (0.96, 3.42)
c. Potier et al[43] (2009)	1RM Ecc Ham strength	0.9 ± 2.2	11	13.8 ± 7.17	11	17.9	2.34 (1.21, 3.47)
d. Timmins et al[47] (2016)	180°/s Ecc Ham PT, Nm	26.87 ± 14.14	14	32.5 ± 17.65	14	22.5	0.34 (−0.41, 1.09
e. Timmins et al[47] (2016)	60°/s Ecc Ham PT, Nm	22.51 ± 15.14	14	30.3 ± 14.97	14	22.4	0.50 (−0.25, 1.26)
f. Total			57		57	100.0	1.06 (0.26, 1.86)

Heterogeneity: $T^2 = 0.59$, $\chi^2_4 = 14.71$, $P = .005$, $I^2 = 73\%$

Test for overall effect: $Z = 2.60$; $P = .009$

Figure 6. Forest plot of the difference in eccentric hamstrings strength between eccentric strength-training and concentric strength-training (control) groups. Abbreviations: CI, confidence interval; Ecc, eccentric; Ham, hamstrings; PT, peak torque; RM, repetition maximum.

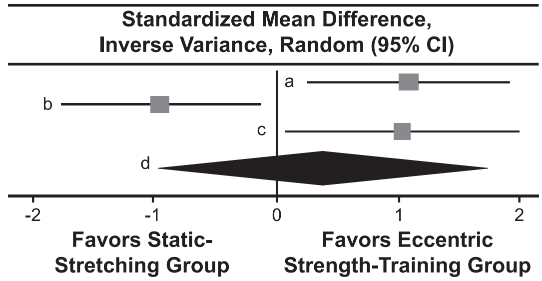


		Usual-Level-of-Activity Group		Eccentric Strength-Training Group			
Study Name	Subgroup Within Study	Mean ± SD	Total, No.	Mean ± SD	Total, No.	Weight, %	Standardized Mean Difference Inverse Variance, Random (95% CI)
a. Bourne et al[38] (2017)	3RM Ham strength HEE, kg	3.5 ± 1.37	10	41 ± 1.46	10	1.2	25.37 (16.55, 34.19)
b. Bourne et al[38] (2017)	3RM Ham strength NHE, kg	3.5 ± 1.37	10	26 ± 1.46	10	2.7	15.22 (9.88, 20.56)
c. Bourne et al[38] (2017)	Max Ecc knee-flexor strength HEE, N	−8.91 ± 10.26	10	110.47 ± 9.88	10	3.9	11.35 (7.33, 15.37)
d. Bourne et al[38] (2017)	Max Ecc knee-flexor strength NHE, N	−8.91 ± 10.26	10	97.38 ± 10.53	10	4.6	9.79 (6.29, 13.29)
e. Delahunt et al[39] (2016)	120°/s Ecc Ham PT, Nm	−1.1 ± 10.75	14	27 ± 10.67	15	8.7	2.55 (1.54, 3.56)
f. Delahunt et al[39] (2016)	120°/s Ecc Ham PT, Nm/kg	−0.01 ± 0.14	14	0.34 ± 0.12	15	8.7	2.62 (1.59, 3.64)
g. Iga et al[40] (2012)	120°/s Ecc Ham PT DOM, Nm	−1 ± 18.79	8	13 ± 19.47	10	8.8	0.70 (−0.27, 1.66)
h. Iga et al[40] (2012)	120°/s Ecc Ham PT NDOM, Nm	5 ± 16.41	8	14 ± 14.56	10	8.8	0.56 (−0.40, 1.51)
i. Iga et al[40] (2012)	240°/s Ecc Ham PT DOM, Nm	−4 ± 21.79	8	9 ± 19	10	8.8	0.61 (−0.35, 1.57)
j. Iga et al[40] (2012)	240°/s Ecc Ham PT NDOM, Nm	4 ± 15.35	8	20 ± 14.77	10	8.7	1.01 (0.01, 2.02)
k. Iga et al[40] (2012)	60°/s Ecc Ham PT DOM, Nm	1 ± 17.79	8	17 ± 19	10	8.8	0.82 (−0.15, 1.80)
l. Iga et al[40] (2012)	60°/s Ecc Ham PT NDOM, Nm	2 ± 16.62	8	20 ± 15.06	10	8.7	1.09 (0.07, 2.10)
m. Ribeiro-Alvares et al[44] (2018)	60°/s Ecc Ham PT, Nm	1.5 ± 13.55	10	16 ± 12.51	10	8.8	1.06 (0.11, 2.02)
n. Ribeiro-Alvares et al[44] (2018)	H:Q functional ratio	0.01 ± 0.03	10	0.08 ± 0.05	10	8.7	1.63 (0.58, 2.67)
o. Total			136		150	100.0	2.72 (1.68, 3.77)

Heterogeneity: $T^2 = 2.98$, $\chi^2_{13} = 120.66$, $P < .001$, $I^2 = 89\%$

Test for overall effect: $Z = 5.12$; $P < .001$

Figure 7. Forest plot of the difference in eccentric hamstrings strength between eccentric strength-training and usual-level-of-activity (control) groups. Abbreviations: CI, confidence interval; DOM, dominant; Ecc, eccentric; H : Q, eccentric hamstrings peak torque to concentric quadriceps peak torque; Ham, hamstrings; HEE, hip-extension exercise; Max, maximal; NDOM, nondominant; NHE, Nordic hamstrings exercise; PT, peak torque; RM, repetition maximum.



Study Name	Subgroup Within Study	Static-Stretching Group		Eccentric Strength-Training Group			
		Mean ± SD	Total, No.	Mean ± SD	Total, No.	Weight, %	Standardized Mean Difference Inverse Variance, Random (95% CI)
a. Sebelien et al[45] (2014)	60°/s Ecc Ham PT, Nm	−10.8 ± 9.99	16	−2.8 ± 4.13	11	33.7	1.10 (0.27, 1.93)
b. Sebelien et al[45] (2014)	H:Q functional ratio	0 ± 0.018	16	−0.02 ± 0.022	11	33.9	−0.95 (−1.76, −0.13)
c. Seymore et al[46] (2017)	60°/s Ecc Ham PT, Nm/kg	−0.08 ± 0.13	10	0.18 ± 0.31	10	32.5	1.05 (0.10, 2.00)
d. Total			42		32	100.0	0.39 (−0.97, 1.75)

Heterogeneity: $T^2 = 1.25$, $\chi^2_2 = 14.89$, $P < .001$, $I^2 = 87\%$

Test for overall effect: $Z = 0.56$; $P = .58$

Figure 8. Forest plot of the difference in eccentric hamstrings strength between eccentric strength-training and static-stretching training (control) groups. Abbreviations: CI, confidence interval; Ecc, eccentric; H : Q, eccentric hamstrings peak torque to concentric quadriceps peak torque; Ham, hamstrings; PT, peak torque.

thought to be linked with the addition of in-parallel sarcomeres, which can positively influence the capacity of a skeletal muscle to generate maximum strength.[25,29] However, increases in muscle thickness and pennation angle may also counter the tendency for fascicle length to increase and thereby decrease the shortening capacity of the muscle.[43,70] Ikegawa et al[71] indicated that the largest pennation angle was associated with the lowest force relative to the muscle cross-sectional area of strength-trained athletes. This result suggested that excessive muscle hypertrophy could affect the pennation angle of skeletal muscle and potentially limit fascicle lengthening and force production. More studies are required to determine the limit beyond which muscle thickness becomes ineffective in increasing muscle strength.

Small et al[72] demonstrated that performing eccentric hamstrings-strengthening exercises in a fatigued state rather than during a warmup resulted in much better eccentric peak torque gains and maintained the eccentric hamstrings peak torque-to-concentric quadriceps peak torque ratio during simulated soccer or rugby match play. The authors postulated that a fatigued training strategy likely induced long-term changes in the ability of the hamstrings to maintain power delivery over prolonged locomotor activity. Interestingly, Lovell et al[42] reported no difference in fascicle length and muscle thickness when EST was performed in a fatigued state after field-training sessions when compared with a core-stability training group. However, an increase in eccentric hamstrings peak torque was present in the eccentric group when EST was performed under the same conditions. This may indicate that fatigue mainly influences the neuromuscular system rather than muscle architecture, and some investigators[73] have recommended neuromuscular exercises (plyometric exercises, landing techniques) in addition to EST to optimize stretch-shortening–cycle muscle function.

Our review provides a better understanding of the chronic LHBF architectural and strength effects of EST that are involved in HSI prevention. Sports and health care specialists should include eccentric strength in the training plan of athletes and target these muscle adaptations to reduce HSI rates. Whereas all eccentric hamstrings training seems to effectively change modifiable HSI risk factors, NHE was the most commonly performed exercise in the literature we searched. The NHE is easy to perform and reproduce, requires a partner but no equipment, and can be included when training large groups. It is a tool that can be used by athletic trainers and possibly in collaboration with coaches and physiotherapists. Athletic trainers and physiotherapists could include a prevention program to minimize HSI in sports involving high-speed running or extreme joint positions. Authors[38–47] have recommended that the intervention protocol involve a body-weight training program performed 2 or 3 times per week for a minimum of 4 to 6 weeks. During each session, after general and hamstrings-specific warmup procedures, athletes should perform 2 to 6 sets of 5 to 12 repetitions, with 30 seconds to 3 minutes of rest between sets. However, data are lacking for the optimal knee range of motion and velocities needed during NHE, and the heterogeneity of the collected data did not allow us to propose a consensus for these variables. Nevertheless, researchers[21,22] have argued that exercises should simulate the load, range of motion, and velocities experienced during the presumably injurious pattern in order to be effective. In other words, we suggest that NHE should preferably be performed with maximum knee range of motion and high velocity, but further research is needed to confirm this hypothesis.

To our knowledge, our systematic review with meta-analysis is the first to describe the effects of EST on LHBF architecture and strength. However, our study had several limitations, and our results must be interpreted with caution. First, all included studies were evaluated as having an unclear or high risk of bias, limiting our confidence in the results. Some investigators did not report baseline outcomes or assessments of population characteristics, and some who compared the groups before the intervention found differences. Evaluators were not always blinded to the athletes' conditions, and bias might have been introduced during the assessment. In addition, in most studies, participants may have pursued a different training protocol than the one to which they were randomly assigned. Second, the exercises and training protocols were diverse. A third limitation was the small number of participants included in the clinical trials. Although we presented well-defined inclusion criteria, we found several methodologic limitations. Participants with variable activity levels were recruited. In addition, participants in the control group received heterogeneous treatments: concentric strength training, core-stability training, stretching, and even no activity. Furthermore, we did not include all architectural outcomes, such as muscle volume, anatomic cross-sectional area, physiological cross-sectional area, and the muscle's aponeurosis. In summary, the limitations of our review could indicate that strength and architectural alterations, as well as exercise recommendations, must be carefully adapted to healthy adults.

Our review addressed the protective mechanisms against HSI provided by EST. A better understanding of this mechanism is sought, considering the implications of both eccentric strength and architectural muscle adaptations. Future research is needed to determine clinical guidelines for selecting exercises, and standardized training methods, especially regarding range of motion and contraction velocity, are necessary to optimize results and reproducibility. Investigators should also focus on compliance, sport-specific prevention programs, and sex-specific adaptations. Finally, the effects of EST on sport performance and the effectiveness of its integration into rehabilitation practices after injury remain unknown.

CONCLUSIONS

This systematic review and meta-analysis offered evidence that EST produced architectural adaptations in the LHBF and increased eccentric hamstrings strength. In healthy adults, EST was associated with increased fascicle length and muscle thickness and decreased pennation angle. The effectiveness of EST in preventing HSI is possibly mediated by the capacity to achieve higher forces and enhanced capacity to support stretch during eccentric muscle actions. However, further studies are needed to confirm these findings, determine guidelines for exercise selection, and standardize training methods for adoption in clinical practice. In summary, strategies for preventing HSI, including EST, should consider both eccentric hamstrings strength and structural adaptations.

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