Evidence-Based Hamstring Injury Prevention and Risk Factor Management

CME

A Systematic Review and Meta-analysis of Randomized Controlled Trials

Samuel S. Rudisill,*†‡ BS, Nathan H. Varady,†§ MD, MBA, Michael P. Kucharik,† BS, Christopher T. Eberlin,† BS, and Scott D. Martin,† MD
Investigation performed at Massachusetts General Hospital, Partners Health System, Boston, Massachusetts, USA

Background: Hamstring injuries are common among athletes. Considering the potentially prolonged recovery and high rate of recurrence, effective methods of prevention and risk factor management are of great interest to athletes, trainers, coaches, and therapists, with substantial competitive and financial implications.

Purpose: To systematically review the literature concerning evidence-based hamstring training and quantitatively assess the effectiveness of training programs in (1) reducing injury incidence and (2) managing injury risk factors.

Study Design: Systematic review and meta-analysis; Level of evidence, 1.

Methods: A computerized search of MEDLINE, CINAHL, Cochrane Central Register of Controlled Trials, and SPORTDiscus with manual screening of selected reference lists was performed in October 2020. Randomized controlled trials investigating methods of hamstring injury prevention and risk factor management in recreational, semiprofessional, and professional adult athletes were included.

Results: Of 2602 articles identified, 108 were included. Eccentric training reduced the incidence of hamstring injury by 56.8% to 70.0%. Concentric hamstring strength increased with eccentric (mean difference [MD], 14.29 N·m; 95% CI, 8.53-20.05 N·m), concentric, blood flow–restricted, whole-body vibration, heavy back squat, FIFA 11 + (Fédération Internationale de Football Association), and plyometric training methods, whereas eccentric strength benefited from eccentric (MD, 26.94 N·m; 95% CI, 15.59-38.30 N·m), concentric, and plyometric training. Static stretching produced greater flexibility gains (MD, 10.89°; 95% CI, 8.92°-12.86°) than proprioceptive neuromuscular facilitation (MD, 9.73°; 95% CI, 6.53°-12.93°) and dynamic stretching (MD, 6.25°; 95% CI, 2.84°-9.66°), although the effects of static techniques were more transient. Fascicle length increased with eccentric (MD, 0.90 cm; 95% CI, 0.53-1.27 cm) and sprint training and decreased with concentric training. Although the conventional hamstring/quadriceps (H/Q) ratio was unchanged (MD, 0.03; 95% CI, –0.01 to 0.06), the functional H/Q ratio significantly improved with eccentric training (MD, 0.10; 95% CI, 0.03-0.16). In addition, eccentric training reduced limb strength asymmetry, while H/Q ratio and flexibility imbalances were normalized via resistance training and static stretching.

Conclusion: Several strategies exist to prevent hamstring injury and address known risk factors. Eccentric strengthening reduces injury incidence and improves hamstring strength, fascicle length, H/Q ratio, and limb asymmetry, while stretching-based interventions can be implemented to improve flexibility. These results provide valuable insights to athletes, trainers, coaches, and therapists seeking to optimize hamstring training and prevent injury.

Keywords: hamstring injury; prevention; risk factor; hamstring strength; hamstring flexibility

Hamstring injury is one of the most common injuries among athletes, representing nearly half of all muscle injuries and 12% to 29% of total injuries.[25,45,100,128] The pathogenesis of hamstring injury is often multifactorial but generally occurs during activities requiring high-speed running[11,14] or stretching to extreme muscle lengths.[12,13] In light of the potentially prolonged absence from sports and the high rate of recurrence, hamstring injuries are of great concern to athletes and sports medicine specialists as there may be substantial competitive and financial implications.[8,11-13,34,37,56] Several risk factors for

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hamstring injury have been identified, including deficits in strength and flexibility, a reduced hamstring/quadriceps (H/Q) ratio, and asymmetry in strength and flexibility between limbs.[47,109] Numerous training programs have been designed to address these risk factors and prevent hamstring injury. For example, eccentric training,[‖] proprioceptive neuromuscular facilitation (PNF),[¶] neurodynamic sliding,[27,42,84,101,113,118] vibration therapy,[49,51,73,99,108,127] and stretching[#] are increasingly being implemented by athletes, trainers, coaches, and therapists. Nevertheless, optimal methods for hamstring injury prevention remain unclear, and prevalence has continued to rise in recent years.[46]

The purpose of this study was therefore to systematically review the literature concerning evidence-based hamstring training and quantitatively assess the effectiveness of training programs in (1) reducing injury incidence and (2) managing injury risk factors.

METHODS

Research Framework

This systematic review and meta-analysis was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.[92] A protocol was registered with the PROSPERO database (CRD42021224381) before data extraction.

Eligibility Criteria

Articles examining hamstring injury prevention and risk factor management were considered eligible if they met each of the following criteria: (1) a randomized controlled trial (RCT) study design was used; (2) participants were noninjured adults (≥18 years of age) involved in recreational, semiprofessional, or professional sports; (3) the authors evaluated an intervention for hamstring injury prevention or mitigation of risk factors; and (4) reported outcomes included injury incidence, strength, flexibility, fascicle length, H/Q ratio, and/or limb asymmetries. To eliminate potential carryover effects influencing results of crossover studies, only RCTs employing a parallel design were included. Studies investigating patients with previous hamstring injuries or not available in English were excluded.

Information Sources and Search

In October 2020, MEDLINE (1946-present), CINAHL (1981-present), Cochrane Central Register of Controlled Trials (1996-present), and SPORTDiscus (1949-present) were queried. To identify pertinent articles, a comprehensive search strategy was developed using applicable Medical Subject Headings terms and keywords as described in Appendix 1 (available in the online version of this article). Further manual screening of selected article reference lists ascertained any additional relevant articles not retrieved by the computerized search.

Study Selection

Study eligibility was assessed using a specialized systematic review management software (Covidence; Veritas Health Innovation). Two reviewers (S.S.R. and M.P.K.) independently screened all articles based on title and abstract, and potentially eligible articles subsequently underwent full-text review before final determination of study inclusion. Any disagreements between reviewers were resolved by discussion.

Data Collection

Information on study design, methods, population, intervention(s), and outcome measures, including hamstring injury incidence, strength, flexibility, fascicle length, H/Q ratio, and limb asymmetries, was collected using a custom data extraction form developed in accordance with the *Cochrane Handbook for Systematic Reviews of Interventions*.[38] All data were extracted by a single reviewer (S.S.R.) and verified by a second reviewer (M.P.K.).

Risk of Bias Assessment

Risk of bias was assessed based on participant randomization, assignment to intervention, availability of outcome data, outcome measurement, and selection of reported results using the revised Cochrane Risk of Bias Tool for Randomized Trials.[121] The overall risk of bias for each study was categorized as “low,” “some concerns,” or “high.”

‖References 7, 10, 23, 26, 43, 53, 57, 58, 66, 69, 71, 76, 85, 86, 88, 89, 91, 95, 96, 105, 107, 109-112, 114-116, 119, 125, 128, 131.

¶References 3, 6, 22, 35, 40, 41, 48, 52, 59, 72, 77, 78, 98, 103, 104, 120, 122, 123, 129, 133, 134.

#References 2, 15, 18-21, 28, 29, 32, 50, 54, 60, 61, 68, 75, 81, 83, 90, 93, 94, 97, 130, 132.

*Address correspondence to Samuel S. Rudisill, BS, Sports Medicine Center, Department of Orthopaedic Surgery, Massachusetts General Hospital, Partners Health System, 175 Cambridge Avenue, Suite 400, Boston, Massachusetts, 02114 (email: srudisill24@gmail.com).

†Sports Medicine Center, Department of Orthopaedic Surgery, Massachusetts General Hospital, Partners Health System, Boston, Massachusetts, USA.

‡Rush Medical College of Rush University, Chicago, Illinois, USA.

§Department of Orthopedic Surgery, Hospital for Special Surgery, New York, New York, USA.

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Meta-analysis

Meta-analyses were performed for interventions and outcomes for which there were at least 3 comparable studies with requisite data available. For continuous variables, pooled effects were generated by means of inverse variance random-effects meta-analysis using the DerSimonian-Laird method[44] to estimate between-study variance. Forest plots and mean differences (MDs) with 95% CIs are presented. Heterogeneity was independently assessed with the Higgins and Thompson I^2, DerSimonian-Laird τ^2, and Cochran Q test of heterogeneity.[33,63] Similarly, for analysis of injury incidence, random-effects meta-analysis with the Mantel-Haenszel method[79] and Paule-Mandel estimator[102] was implemented, and the pooled relative risk (RR) with 95% CI was determined. Analyses were performed in R Version 4.0.5 with the meta package.[17] $P < .05$ was considered statistically significant.

RESULTS

Study Selection

The computerized search retrieved 2483 articles, with an additional 119 identified on manual screening. After removing duplicates, 1965 articles were evaluated according to title and abstract, and 194 were retained for full-text review. Of these, 86 articles were excluded for failure to satisfy the inclusion criteria; thus, 108 were included (Figure 1).

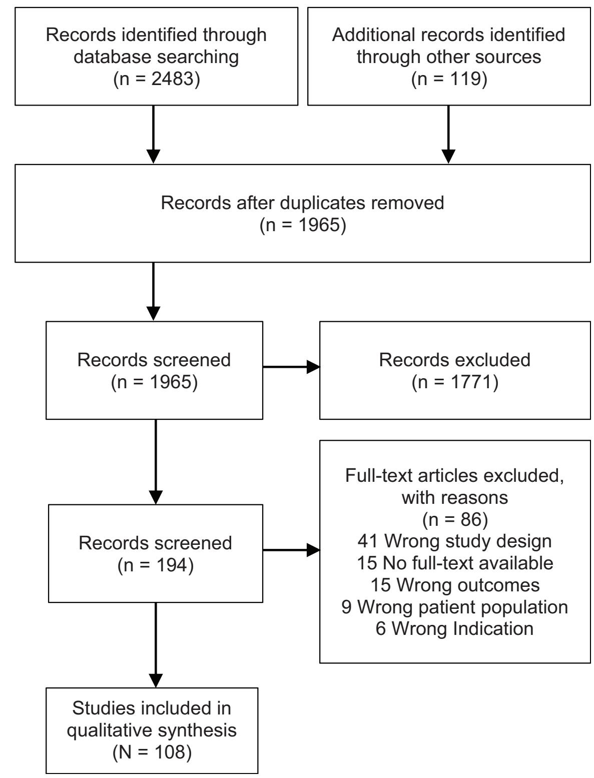

Figure 1. Study flowchart.

Study Characteristics

Included studies investigated between 14 and 942 recreational, semiprofessional, or professional athletes with mean ages of 18.0 to 36.1 years. With follow-up ranging from 0 to 52 weeks, studies evaluated the effects of eccentric training,[**] stretching,[††] specialized training programs,[§§] neurodynamic sliding,[27,42,84,101,113,118] vibration therapy,[49,51,73,99,108,127] massage,[4,64,65,80,82] resistance training,[5,70] dry needling,[55,62] kinesiotaping,[87] and blood flow–restricted training[1] on hamstring injury prevention and risk factor management. Efficacy was assessed according to injury incidence,[10,53,105,128] strength,[||||] flexibility,[¶¶] fascicle length,[##] H/Q ratio,[a] and limb asymmetry.[5,7,78,131] A summary of study characteristics is provided in Table 1.

Risk of Bias

Of 108 RCTs included, 82 were judged to have a low risk of bias, 19 raised some concerns, and 7 were evaluated as high risk. In most cases, risk was attributable to inadequate randomization and concealment of the participant allocation process or missing outcome data for >5% of patients.

Synthesis of Results

Hamstring Injury Prevention

Prevention of hamstring injury was directly assessed in 4 studies that measured the effect of eccentric strengthening on injury incidence (see Appendix Table A1, available online). Athletes participating in soccer[10,105,128] or Australian football[53] who completed 10 to 13 weeks of eccentric training were significantly less likely to experience hamstring injury during the competitive season compared with those performing ordinary training (n = 1654; RR, 0.34; 95% CI, 0.25-0.46; I^2 = 0%) (Figure 2), with individual

[**]References 7, 10, 23, 26, 43, 53, 57, 58, 66, 69, 71, 76, 85, 86, 88, 89, 91, 95, 96, 105, 107, 109-112, 114-116, 119, 125, 128, 131.

[††]References 2, 15, 18-21, 28, 29, 32, 50, 54, 60, 61, 68, 75, 81, 83, 90, 93, 94, 97, 130, 132.

[‡‡]References 3, 6, 22, 35, 40, 41, 48, 52, 59, 72, 77, 78, 98, 103, 104, 120, 122, 123, 129, 133, 134.

[§§]References 9, 30, 31, 39, 67, 74, 106, 117, 126.

[||||]References 1, 2, 5, 7, 9, 10, 20, 23, 26, 29, 39, 43, 57, 58, 62, 64, 66, 67, 69-71, 73, 74, 76, 83, 85, 86, 89, 91, 93-96, 106, 107, 109-112, 115-117, 119, 125, 126, 131.

[¶¶]References 2-4, 6, 15, 18, 19, 21, 22, 27-29, 31, 32, 35, 40-43, 48-52, 54, 55, 58-62, 64, 65, 68, 72, 73, 75, 77, 80-84, 87, 90, 91, 93, 94, 97-99, 101, 103, 104, 107-109, 113, 114, 117, 118, 120, 122, 123, 127, 129, 130, 132-134.

[##]References 4, 23, 57, 76, 85, 86, 88, 106, 107, 109, 115, 116, 125.

[a]References 2, 5, 9, 26, 30, 43, 58, 73, 86, 89, 91, 109, 110, 115, 126, 131.

TABLE 1
Summary of Included Studies[a]

Article	Risk of Bias	Intervention(s)	Sample Size	Duration of Follow-up, wk	Outcomes Measured: Injury Incidence Rate	Hamstring Strength	Flexibility	Fascicle Length	H/Q Ratio	Limb Asymmetry
Abe et al (2006)[1]	Low	(1) Kaatsu walk training with blood flow restriction	9	3		●				
		(2) Control—walk training	9							
Aguilar et al (2012)[2]	Low	(1) Dynamic warm-up	15	0		●	●		●	
		(2) Static stretching	15							
		(3) Control—no intervention	15							
Ahmed et al (2015)[3]	Low	(1) PNF + moist heat	15	2			●			
		(2) Static stretching + moist heat	15							
		(3) Control—moist heat	15							
Akazawa et al (2016)[4]	Low	(1) Self-massage at MTJ	37	12			●	●		
		(2) Control—no intervention	37							
Aktug (2020)[5]	Low	(1) TheraBand strength exercises	13	10		●			●	●
		(2) Control—normal training routine	14							
Alshammari et al (2019)[6]	Low	(1) Neurodynamic technique + static stretching	20	0			●			
		(2) Passive + active stretching	20							
		(3) Passive stretching	20							
Anastasi and Hamzeh (2011)[7]	Low	(1) NHE	13	10		●				●
		(2) Control—no intervention	11							
Arsenis et al (2020)[9]	Low	(1) FIFA 11+ warm-up program	16	8		●			●	
		(2) Control—normal warm-up	16							
Askling et al (2003)[10]	Low	(1) Hamstring training with eccentric overload	15	46	●	●				
		(2) Control—normal training	15							
Ayala et al (2010)[15]	Low	(1) Static stretching 12 × 15 s, 3 d/wk	35	12			●			
		(2) Static stretching 6 × 30 s, 3 d/wk	47							
		(3) Static stretching 4 × 45 s, 3 d/wk	39							
		(4) Control—no intervention	29							
Bandy et al (1997)[19]	Low	(1) Static stretching 3 × 60 s, 5 d/wk	18	6			●			
		(2) Static stretching 3 × 30 s, 5 d/wk	19							
		(3) Static stretching 1 × 60 s, 5 d/wk	18							
		(4) Static stretching 1 × 30 s, 5 d/wk	18							
		(5) Control—no intervention	20							
Bandy et al (1998)[18]	Low	(1) Passive static stretching	19	6			●			
		(2) Dynamic ROM stretching	19							
		(3) Control—no intervention	20							
Barbosa et al (2020)[20]	Low	(1) Dynamic stretching	15	4		●				
		(2) Static stretching	15							
		(3) Control—no intervention	15							
Berenbaum et al (2015)[21]	Some concerns	(1) Dynamic stretching	8	3			●			
		(2) Static stretching	9							
		(3) Control—no intervention	5							
Bonnar et al (2004)[22]	Low	(1) PNF 3-s hold-relax	20	0			●			
		(2) PNF 6-s hold-relax	20							
		(3) PNF 10-s hold-relax	20							
Bourne et al (2017)[23]	Some concerns	(1) NHE	10	10		●		●		
		(2) Hip extension exercise	10							
		(3) Control—no intervention	10							
Brughelli et al (2010)[26]	Low	(1) Eccentric training	13	4		●			●	
		(2) Control—normal soccer training	11							
Castellote-Caballero et al (2014)[27]	Low	(1) Neurodynamic sliding	40	0			●			
		(2) Passive stretching	40							
		(3) Passive mobilization of foot joints	40							
Chan et al (2001)[28]	Some concerns	(1) 8-wk static stretching protocol	10	4/8			●			
		(2) 4-wk static stretching protocol	10							
		(3) Control A—8 wk no stretching	10							
		(4) Control B—4 wk no stretching	10							
Chen et al (2018)[29]	Some concerns	(1) Jogging + open kinetic chain stretching	12	0		●	●			
		(2) Jogging + closed chain kinetic stretching	12							
		(3) Control—jogging	12							
Cherni et al (2019)[30]	Some concerns	(1) Plyometric training	13	8					●	
		(2) Control—normal training	12							
Chinnavan et al (2015)[31]	Low	(1) Pilates training	15	4			●			
		(2) Control—ballistic, PNF, or static stretching	15							
Cipriani et al (2012)[32]	Low	(1) Static stretching twice daily × 7 d/wk	11	8			●			
		(2) Static stretching once daily × 7 d/wk	12							
		(3) Static stretching twice daily × 3-4 d/wk	11							
		(4) Static stretching once daily × 3-4 d/wk	10							
		(5) Control—no intervention	9							
Cornelius and Rauschuber (1987)[35]	Low	(1) PNF 6 s MVIC during hold-relax	20	0			●			
		(2) PNF 10 s MVIC during hold-relax	20							
Daneshjoo et al (2012)[39]	Low	(1) FIFA 11+ training program	12	8		●				
		(2) HarmoKnee training program	12							
		(3) Control—normal training	12							
Dastmenash et al (2010)[40]	Some concerns	(1) WBV	10							
		(2) PNF + static stretching	11	6			●			
		(3) WBV + PNF + static stretching	10							
Davis et al (2005)[41]	Low	(1) Active stretching	5	4			●			
		(2) Static stretching	5							
		(3) PNF	5							
		(4) Control—no intervention	4							
De Ridder et al (2020)[42]	Some concerns	(1) Neurodynamic sliding	25	10			●			
		(2) Control—static stretching	25							
Delvaux et al (2020)[43]	Low	(1) Eccentric training	14	6		●	●			
		(2) Control—no intervention	13							

(continued)

TABLE 1
(continued)

					Outcomes Measured					
Article	Risk of Bias	Intervention(s)	Sample Size	Duration of Follow-up, wk	Injury Incidence Rate	Hamstring Strength	Flexibility	Fascicle Length	H/Q Ratio	Limb Asymmetry
Entyre and Lee (1988)[48]	Some concerns	(1) PNF	74[b]	12			●			
		(2) PNF + antagonist contraction during relax phase								
		(3) Static stretching								
		(4) Control—no intervention								
Fagnani et al (2006)[49]	High	(1) WBV	13	8			●			
		(2) Control—no intervention	11							
Fasen et al (2009)[50]	Some concerns	(1) Active knee extension stretching	18	8			●			
		(2) Passive knee extension stretching	16							
		(3) Active straight leg raise stretching	16							
		(4) Passive straight leg raise stretching	19							
		(5) Control—no intervention	18							
Feland and Marin (2004)[52]	Low	(1) PNF at 100% MVIC	15	0.71			●			
		(2) PNF at 60% MVIC	17							
		(3) PNF at 20% MVIC	18							
		(4) Control—no intervention	12							
Feland et al (2010)[51]	Low	(1) WBV + static stretching	13	7			●			
		(2) Static stretching	12							
		(3) Control—no intervention	9							
Gabbe et al (2006)[53]	Low	(1) Eccentric training	114	12	●					
		(2) Control—stretching and ROM training	106							
Gajdosik (1991)[54]	Low	(1) Static stretching	12	3			●			
		(2) Control—no intervention	12							
Geist et al (2017)[55]	Low	(1) Experimental limb—dry needling	13	6			●			
		(2) Experimental limb—stretching	14							
		(3) Control limb—dry needling	13							
		(4) Control limb—stretching	14							
Guex et al (2016)[57]	Low	(1) Eccentric training at short muscle lengths	11	3		●		●		
		(2) Eccentric training at long muscle lengths	11							
Guex et al (2016)[58]	Low	(1) Swing phase-specific eccentric training	10	6		●	●		●	
		(2) Control—no intervention	10							
Gunn et al (2019)[59]	High	(1) PNF	23	0			●			
		(2) Instrument-assisted soft tissue mobilization	17							
		(3) Control—static stretching	40							
Halbertsma and Goeken (1994)[60]	Some concerns	(1) Static stretching	7	4			●			
		(2) Control—no intervention	7							
Hartig and Henderson (1999)[61]	Low	(1) Hamstring-specific stretching	150	13			●			
		(2) Control—no intervention	148							
Haser et al (2017)[62]	Low	(1) Dry needling + water pressure massage	10	4		●	●			
		(2) Placebo laser + water pressure massage	10							
		(3) Control—no intervention	9							
Hodgson et al (2018)[64]	Low	(1) Roller massage 6 times/wk	7	4		●	●			
		(2) Roller massage 3 times/wk	8							
		(3) Control—no intervention	8							
Hopper et al (2005)[65]	Low	(1) Dynamic soft tissue mobilization	15	0			●			
		(2) Soft tissue massage	15							
		(3) Control—no intervention	15							
Iga et al (2012)[66]	Low	(1) NHE	10	4		●				
		(2) Control—no intervention	8							
Janusevicius et al (2017)[67]	Some concerns	(1) High-load concentric-eccentric resistance training	8	5		●				
		(2) High-load concentric resistance training	9							
		(3) High-velocity concentric-eccentric resistance training	8							
Johnson et al (2011)[68]	Low	(1) Static stretching 9 × 10 s	14	6			●			
		(2) Static stretching 3 × 30 s	12							
		(3) Control—no intervention	8							
Jonhagen et al (2009)[69]	Some concerns	(1) Walking forward lunge exercise	11	6		●				
		(2) Jumping forward lunge exercise	10							
		(3) Control—no intervention	11							
Kamandulis et al (2020)[70]	Low	(1) Low-load, high-velocity resistance training	10	5		●				
		(2) Control—no intervention	8							
Kaminski and Wabbersen (1998)[71]	Low	(1) Concentric training	9	6		●				
		(2) Eccentric training	9							
		(3) Control—no lower extremity training	9							
Kannan and Winser (2011)[72]	Low	(1) PNF + icing	10	1			●			
		(2) Static stretching + icing	10							
		(3) Control—static stretching	10							
Karatrantou et al (2013)[73]	Low	(1) WBV	13	3		●	●		●	
		(2) Control—no intervention	13							
Krishna et al (2019)[74]	Low	(1) Plyometric training	21	12		●				
		(2) Control—normal training	21							
LaRoche and Connolly (2006)[75]	Low	(1) Ballistic stretching	10	4			●			
		(2) Static stretching	9							
		(3) Control—no intervention	10							
Lovell et al (2018)[76]	Low	(1) NHE before field training	14	12		●		●		
		(2) NHE after field training	16							
		(3) Control—core stability exercise	12							
Lucas and Koslow (1984)[77]	High	(1) PNF	63[b]	3			●			
		(2) Dynamic stretching								
		(3) Static stretching								
Makaruk et al (2010)[78]	Some concerns	(1) Isometric strength training	10	4						●
		(2) Static stretching	10							
		(3) Control—no intervention	10							

(continued)

TABLE 1
(continued)

					Outcomes Measured					
Article	Risk of Bias	Intervention(s)	Sample Size	Duration of Follow-up, wk	Injury Incidence Rate	Hamstring Strength	Flexibility	Fascicle Length	H/Q Ratio	Limb Asymmetry
Markovic (2015)[80]	Low	(1) Foam rolling	10	0.14			●			
		(2) Fascial abrasion technique	10							
Marques et al (2009)[81]	High	(1) Static stretching 1 time/wk	10	4			●			
		(2) Static stretching 3 times/wk	11							
		(3) Static stretching 5 times/wk	10							
Marr et al (2011)[82]	Low	(1) Bowen technique	60	1			●			
		(2) Control—no intervention	56							
Marshall et al (2011)[83]	Low	(1) Static stretching	11	4		●	●			
		(2) Control—no intervention	11							
Martins et al (2019)[84]	Low	(1) Neural gliding	23	0.14			●			
		(2) Neural tensioning	25							
Marusic et al (2020)[85]	Low	(1) Eccentric training	18	6		●		●		
		(2) Control—no intervention	16							
Medeiros et al (2020)[86]	Low	(1) NHE 1 time/wk	15	8		●		●	●	
		(2) NHE 2 times/wk	17							
Medeni et al (2015)[87]	High	(1) Static stretching with kinesiotaping	15	0			●			
		(2) Control—static stretching	15							
Mendiguchia et al (2015)[89]	Low	(1) Hamstring-emphasized neuromuscular training	27	7				●		
		(2) Control—normal training	24							
Mendiguchia et al (2020)[88]	Low	(1) NHE	12	6		●			●	
		(2) Sprint training	10							
		(3) Control—normal soccer training	10							
Meroni et al (2010)[90]	Low	(1) Active stretching	12	10			●			
		(2) Static stretching	10							
Mjolsnes et al (2004)[91]	Some concerns	(1) NHE	11	10		●	●		●	
		(2) Concentric hamstring exercise	10							
Muanjai et al (2017)[94]	Low	(1) Stretching to point of pain	13	4		●	●			
		(2) Stretching to point of discomfort	13							
Muanjai et al (2017)[93]	Low	(1) Stretching to point of pain	11	0.14		●	●			
		(2) Stretching to point of discomfort	11							
Naclerio et al (2013)[95]	Low	(1) Injury prevention training program	10	4		●				
		(2) Control—no intervention	10							
Naclerio et al (2015)[96]	Low	(1) Eccentric training program	11	6		●				
		(2) Unstable squatting	11							
		(3) Control—no intervention	10							
Nishikawa et al (2015)[97]	Low	(1) Active stretching	18	0			●			
		(2) Passive stretching	18							
		(3) Control—no intervention	18							
O'Hora et al (2011)[98]	Low	(1) PNF	15	0			●			
		(2) Static stretching	15							
		(3) Control—no intervention	15							
Olivares-Arancibia et al (2018)[99]	Low	(1) WBV + static stretching	23	1			●			
		(2) Static stretching	23							
		(3) Control—no intervention	24							
Pagare et al (2014)[101]	Low	(1) Neurodynamic sliding	15	1			●			
		(2) Static stretching	15							
Payla et al (2018)[103]	Some concerns	(1) Muscle energy technique	20	0			●			
		(2) Passive stretching	20							
Perez-Bellmunt et al (2019)[104]	Low	(1) PNF stretching with electrostimulated contraction	15	5			●			
		(2) PNF stretching with voluntary contraction	15							
Petersen et al (2011)[105]	Low	(1) NHE	461	52	●					
		(2) Control—no intervention	481							
Pollard et al (2019)[106]	Low	(1) NHE with bodyweight	10	10		●		●		
		(2) NHE with added weight	10							
		(3) Razor hamstring curl exercise	10							
Potier et al (2009)[107]	Low	(1) Eccentric training	11	8		●	●	●		
		(2) Control—no intervention	11							
Rawtani et al (2019)[108]	Low	(1) Matrix rhythm therapy	15	3			●			
		(2) Passive stretching	15							
Ribeiro-Alvares et al (2018)[109]	Low	(1) NHE	10	4		●	●	●	●	
		(2) Control—no intervention	10							
Ruas et al (2018)[110]	Low	(1) Concentric quadriceps, concentric hamstrings training	10	6		●			●	
		(2) Eccentric quadriceps, eccentric hamstrings training	10							
		(3) Concentric quadriceps, eccentric hamstrings training	10							
		(4) Control—no intervention	10							
Ryan et al (1991)[111]	High	(1) Eccentric training	17	6		●				
		(2) Control—no intervention	17							
Salci et al (2013)[112]	Low	(1) NHE	13	10		●				
		(2) Control—no intervention	12							
Satkunskiene et al (2020)[113]	Low	(1) Neurodynamic gliding	11	0			●			
		(2) Static stretching	11							
Sethi et al (2012)[114]	Some concerns	(1) Eccentric training	15	6			●			
		(2) Static stretching	15							
		(3) Control—no intervention	15							
Severo-Silveira et al (2021)[115]	Some concerns	(1) Progressive NHE training	10	8		●		●	●	
		(2) Constant NHE training	11							
Seymore et al (2017)[116]	Low	(1) NHE	10	6		●		●		
		(2) Static stretching	10							
Shariat et al (2017)[117]	Low	(1) Heavy back squat training	11	9		●	●			
		(2) Light back squat training	11							

(continued)

TABLE 1
(continued)

Article	Risk of Bias	Intervention(s)	Sample Size	Duration of Follow-up, wk	Outcomes Measured: Injury Incidence Rate	Hamstring Strength	Flexibility	Fascicle Length	H/Q Ratio	Limb Asymmetry
Sharma et al (2016)[118]	Low	(1) Neurodynamic sliding + static stretching	20	1			●			
		(2) Neurodynamic tensioning + static stretching	20							
		(3) Control—static stretching	20							
Siddle et al (2019)[119]	Low	(1) NHE	7	9		●				
		(2) Control—no intervention	7							
Spernoga et al (2001)[120]	Low	(1) Modified hold-relax stretching	15	0			●			
			15							
		(2) Control—no intervention								
Sullivan et al (1992)[122]	Low	(1) Static stretching with anterior pelvic tilt	5	2			●			
		(2) PNF with anterior pelvic tilt	5							
		(3) Static stretching with posterior pelvic tilt	5							
		(4) PNF with posterior pelvic tilt	5							
Tanigawa (1972)[123]	High	(1) PNF	10	4			●			
		(2) Passive stretching	10							
		(3) Control—no intervention	10							
Timmins et al (2016)[125]	Low	(1) Concentric hamstrings training	14	10		●		●		
		(2) Eccentric hamstrings training	14							
Tsang and Dipasquale (2011)[126]	Low	(1) Plyometric training	11	6		●			●	
		(2) Control—no intervention	14							
van den Tillaar (2006)[127]	Low	(1) WBV + PNF	10	4			●			
		(2) Control—PNF only	8							
van der Horst et al (2015)[128]	Low	(1) NHE	292	52	●					
		(2) Control—no intervention	287							
Vidhi et al (2014)[129]	Some concerns	(1) PNF	30	0.43			●			
		(2) Neurodynamic stretching with Slump technique	30							
Webright et al (1997)[130]	Some concerns	(1) Active knee extension stretching	11	6			●			
		(2) Static stretching	15							
		(3) Control—no intervention	14							
Whyte et al (2021)[131]	Low	(1) Hip extension exercise	13	4		●			●	●
		(2) NHE	13							
Wiemann and Hahn (1997)[132]	Low	(1) Resistance training at 70% MVIC	12	0			●			
			16							
		(2) Ballistic stretching	14							
		(3) Static stretching	12							
		(4) Stationary cycling	15							
		(5) Control—no intervention								
Yildirim et al (2016)[133]	Low	(1) PNF	6	4			●			
		(2) Mulligan traction straight leg raise	8							
		(3) Static stretching	5							
		(4) Control—no intervention	7							
Yuktasir and Kaya (2009)[134]	Low	(1) PNF	9	6			●			
		(2) Passive stretching	10							
		(3) Control—no intervention	9							

[a]FIFA, Fédération Internationale de Football Association; H/Q, hamstrings/quadriceps; MTJ, musculotendinous junction; MVIC, maximum voluntary isometric contraction; NHE, Nordic hamstring exercise; PNF, proprioceptive neuromuscular facilitation; ROM, range of motion; WBV, whole-body vibration.
[b]The number of participants allocated to each group was not reported.

studies reporting 56.8% to 70.0% incidence reduction. However, severity of injuries incurred did not differ, and compliance was limited by muscle soreness associated with eccentric exercise.[105,128]

Risk Factor Management

Strength. Hamstring strength was reported as an outcome measure by 46 studies (Appendix Table A2, available online). Interventions increasing concentric strength included concentric,[106,125] blood flow–restricted,[1] resistance,[5,10,67,70] whole-body vibration (WBV),[73] heavy back squat,[67,117] FIFA 11+,[9,39] and plyometric[74,126] training regimens. Eccentric training also improved concentric strength,[b] demonstrating a 14.29 N·m (95% CI, 8.53-20.05 N·m) increase in isokinetic peak torque compared with controls in a meta-analysis of 7 studies (n = 210; I^2 = 5%) (Figure 3A). Stretching,[2,83,93,94] dry needling,[62] and water massage[62] yielded no effect. Eccentric strength similarly benefited from eccentric training,[c] increasing by 26.94 N·m (95% CI, 15.59-38.30 N·m) relative to controls in a sample pooled from 4 studies (n = 119; I^2 = 0%) (Figure 3B). WBV,[73] plyometric,[74] and concentric training[125] programs also increased eccentric strength, while the HarmoKnee training program[39] elicited no effect. Mixed results were reported for FIFA 11+.[9,39] Stretching produced no[2,83,93,94] or detrimental[20,29] effect, with static stretching resulting in greater eccentric strength impairment than dynamic techniques.

Flexibility. A total of 70 studies assessed flexibility as evaluated by straight leg raise or knee extension deficit. Static stretching significantly increased flexibility in 28 of 30 studies,[d] improving straight leg raise by 11.01°

[b]References 7, 26, 43, 58, 69, 71, 85, 86, 88, 111, 112, 115, 125.

[c]References 10, 23, 26, 43, 57, 58, 66, 76, 85, 86, 89, 91, 106, 107, 109, 111, 112, 115, 119, 125, 131.

[d]References 3, 15, 18, 19, 21, 28, 32, 41, 42, 50, 54, 60, 61, 68, 72, 75, 77, 81, 83, 90, 93, 94, 97, 98, 103, 114, 130, 132-134.

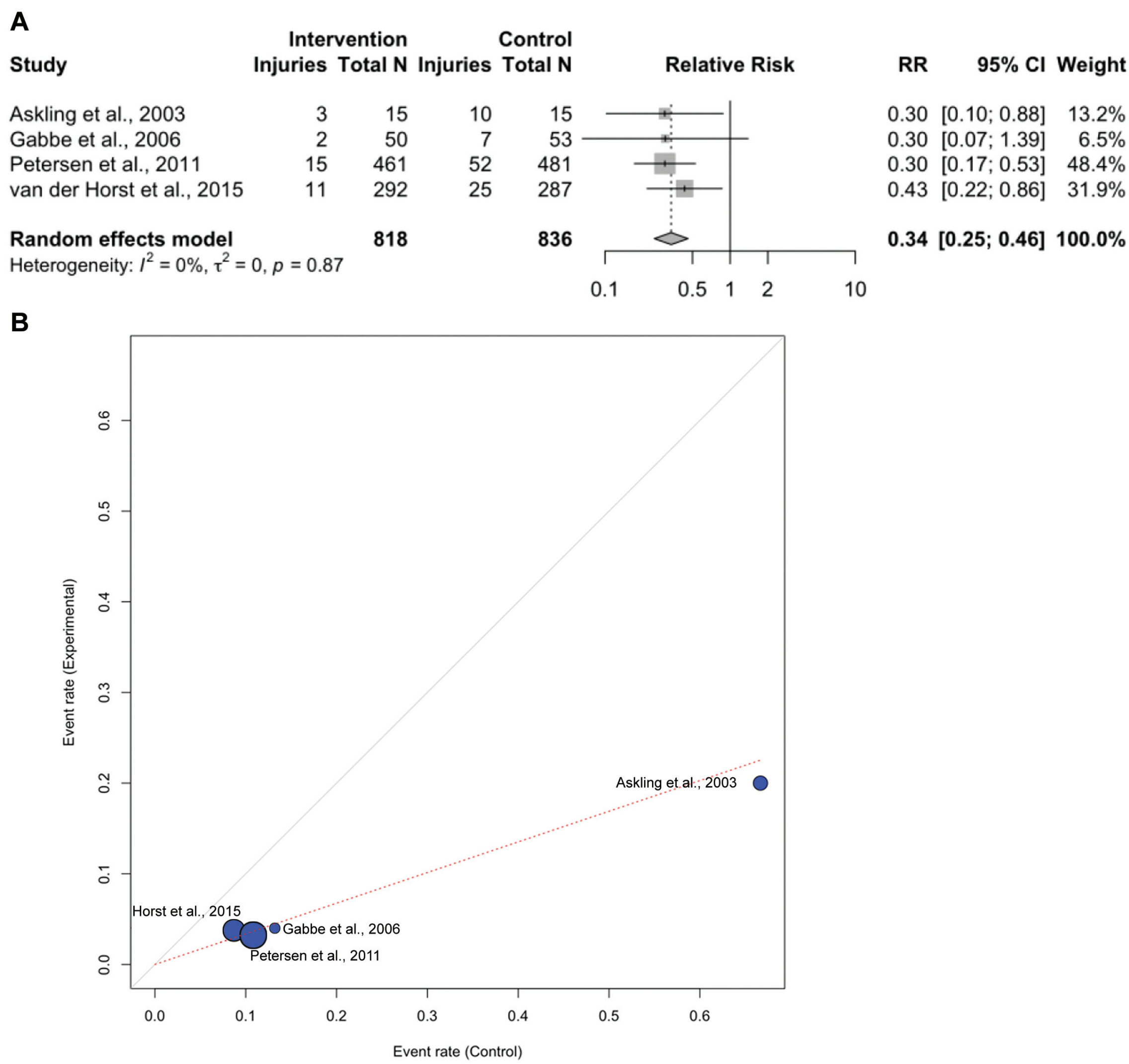

Figure 2. Effect of eccentric training on the incidence of hamstring injury. displayed in terms of relative risk (RR; A) and relative event rate (B).

(95% CI, 6.55°-15.47°; n = 316; I^2 = 68%) (Figure 4A) and knee extension deficit by 10.89° (95% CI, 8.92°-12.86°; n = 191; I^2 = 2%) (Figure 4B) according to meta-analyses of 7 and 4 studies, respectively. Nevertheless, studies exhibited extensive variation in duration, frequency, and intensity of static stretching (see Appendix Table A3, available online). Bandy et al[19] reported that increasing duration or frequency beyond a single 30-second daily session did not elicit greater flexibility gain over 6 weeks, while Hartig and Henderson[61] concluded that multiple sessions per day were required. In contrast, Cipriani et al[32] and Marques et al[81] determined that 3 sessions per week was sufficient. Change in flexibility did not differ based on whether athletes stretched to the point of discomfort or point of pain.[93,94] Nine studies investigated dynamic stretching,[e] of which 5 were amenable to meta-analysis. Dynamic stretching reduced knee extension deficit by 6.25° (95% CI, 2.84°-9.66°; n = 143; I^2 = 57%) (Figure 4C), and although possibly of lesser magnitude than produced by static stretching, this increase in flexibility was less transient. Meroni et al[90] observed athletes performing dynamic stretching to maintain increased flexibility 4 weeks after training, whereas results of static stretching were completely lost. PNF increased flexibility in 16 of 18 studies[f] and achieved a 9.73° (95% CI, 6.53°-12.93°) knee extension deficit reduction compared with controls in a cohort pooled from 4 studies (n = 108; I^2 = 64%) (Figure 4D). Although duration and intensity of PNF technique were not uniform across studies, Bonnar et al[22] found that flexibility gains did not differ between 3-, 6-, and 10-second hold-relax intervals. Additionally, Feland and Marin[52] determined

[e]References 2, 18, 21, 29, 50, 77, 90, 97, 130.

[f]References 3, 6, 22, 35, 41, 48, 52, 59, 77, 98, 103, 104, 120, 122, 123, 129, 133, 134.

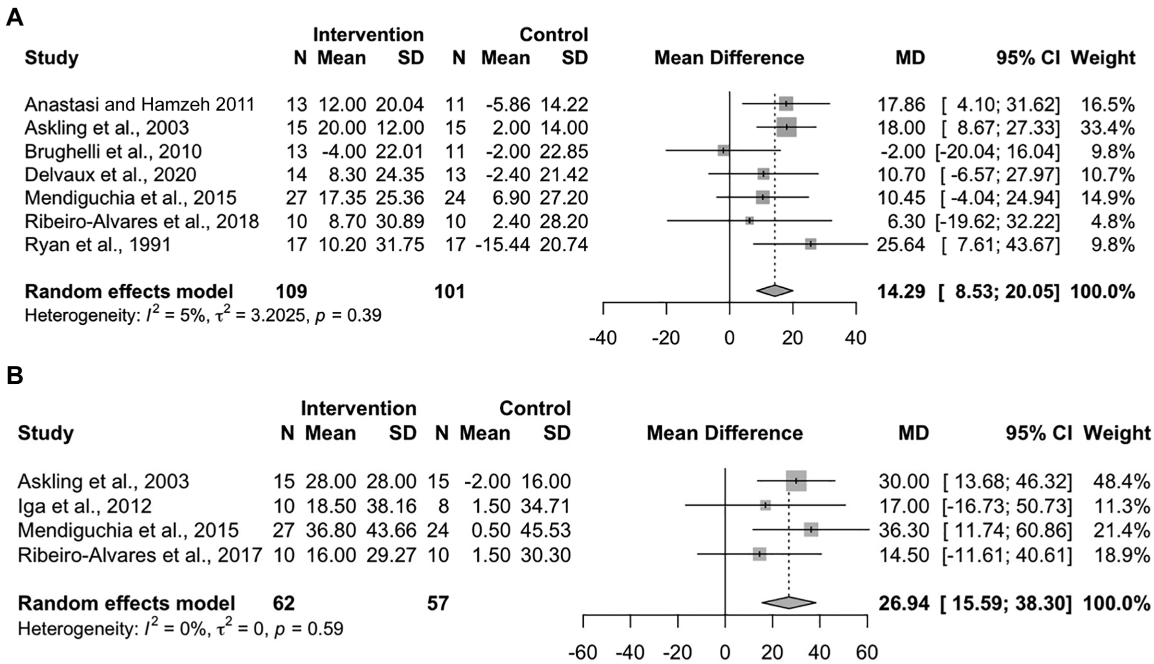

Figure 3. Effect of eccentric training on (A) concentric and (B) eccentric strength. MD, mean difference.

that voluntary isometric contraction at 20% and 100% of maximum was equally effective, suggesting that shorter and less intense methods are most efficient. Flexibility was further optimized by implementing adjunctive WBV,[40] utilizing low-frequency electrical stimulation,[104] or maintaining anterior pelvic tilt throughout the intervention.[122] Additional methods improving flexibility included WBV alone,[40,49,51,73,99,108,127] neurodynamic sliding,[27,42,84,101,113,118] neural tensioning,[84] Pilates,[31] instrument-assisted soft tissue mobilization,[59,65,80] ballistic stretching,[75,132] kinesiotaping,[87] and the Bowen[82] and Mulligan[133] techniques, while consensus could not be reached regarding effects of eccentric training,[43,58,91,107,109,114] dry needling,[55,62] or massage.[4,64]

Fascicle Length. Thirteen studies included fascicle length as an outcome (see Appendix Table A4, available online). The most popular intervention was eccentric training, which demonstrated improvement in 11 of 12 studies.[g] Fascicle length increased by an average of 0.90 cm (95% CI, 0.53-1.27 cm) relative to controls in a meta-analysis of 5 studies (n = 124; I^2 = 0%) (Figure 5), with progressive training regimens[115] and exercises focused at long muscle lengths[57] yielding the greatest improvements. Mendiguchia et al[88] found sprint training to be superior to eccentric training, generating a 16.2% increase in fascicle length compared with 7.4% with Nordic hamstring exercise. In contrast, concentric training was associated with a 10.7% reduction after 10 weeks of training,[125] while self-massage at the musculotendinous junction had no effect.[4]

[g]References 23, 57, 76, 85, 86, 88, 106, 107, 109, 115, 116, 125.

H/Q Ratio. The H/Q ratio was evaluated by 16 studies[h], appraised according to conventional and/or functional metrics (see Appendix Table A5, available online). The conventional H/Q ratio, defined as a comparison of concentric hamstring and concentric quadriceps peak torques, improved in 5 of 12 studies.[i] Although results of eccentric training were variable,[26,58,86,89,109,110,115] analysis of data pooled from 4 studies[26,58,89,109] identified no significant effect (n = 115; MD = 0.03; 95% CI, –0.01 to 0.06; I^2 = 41%) (Figure 6A). Mixed results were also reported for plyometric[30,126] and FIFA 11 +[9] training programs, while the conventional H/Q ratio was unchanged by stretching,[2] resistance,[5] or concentric training.[110] Conversely, the functional H/Q ratio, defined as a comparison of eccentric hamstring and concentric quadriceps peak torques, improved in 10 of 12 studies.[j] Eccentric training facilitated significant effects in 9 of 9 studies[k] and demonstrated an increase in the functional H/Q ratio of 0.10 (95% CI, 0.03 to 0.16) across a cohort pooled from 3 studies[43,58,109] (n = 67; I^2 = 0%) (Figure 6B). Notably, however, Medeiros et al[86] observed significant effects only for athletes participating in at least 2 eccentric training sessions per week, and Severo-Silveira et al[115] determined that a progressive protocol was required. The functional H/Q ratio was not affected by stretching,[2] FIFA 11 + ,[9] or concentric training[110] programs.

Limb Asymmetry. Four studies[5,7,78,131] aimed to reduce limb asymmetries (see Appendix Table A6, available

[h]References 2, 5, 9, 26, 30, 43, 58, 73, 86, 89, 91, 109, 110, 115, 126, 131.
[i]References 2, 5, 9, 26, 30, 58, 86, 89, 109, 110, 115, 126.
[j]References 2, 9, 43, 58, 73, 86, 89, 91, 109, 110, 115, 131.
[k]References 43, 58, 86, 89, 91, 109, 110, 115, 131.

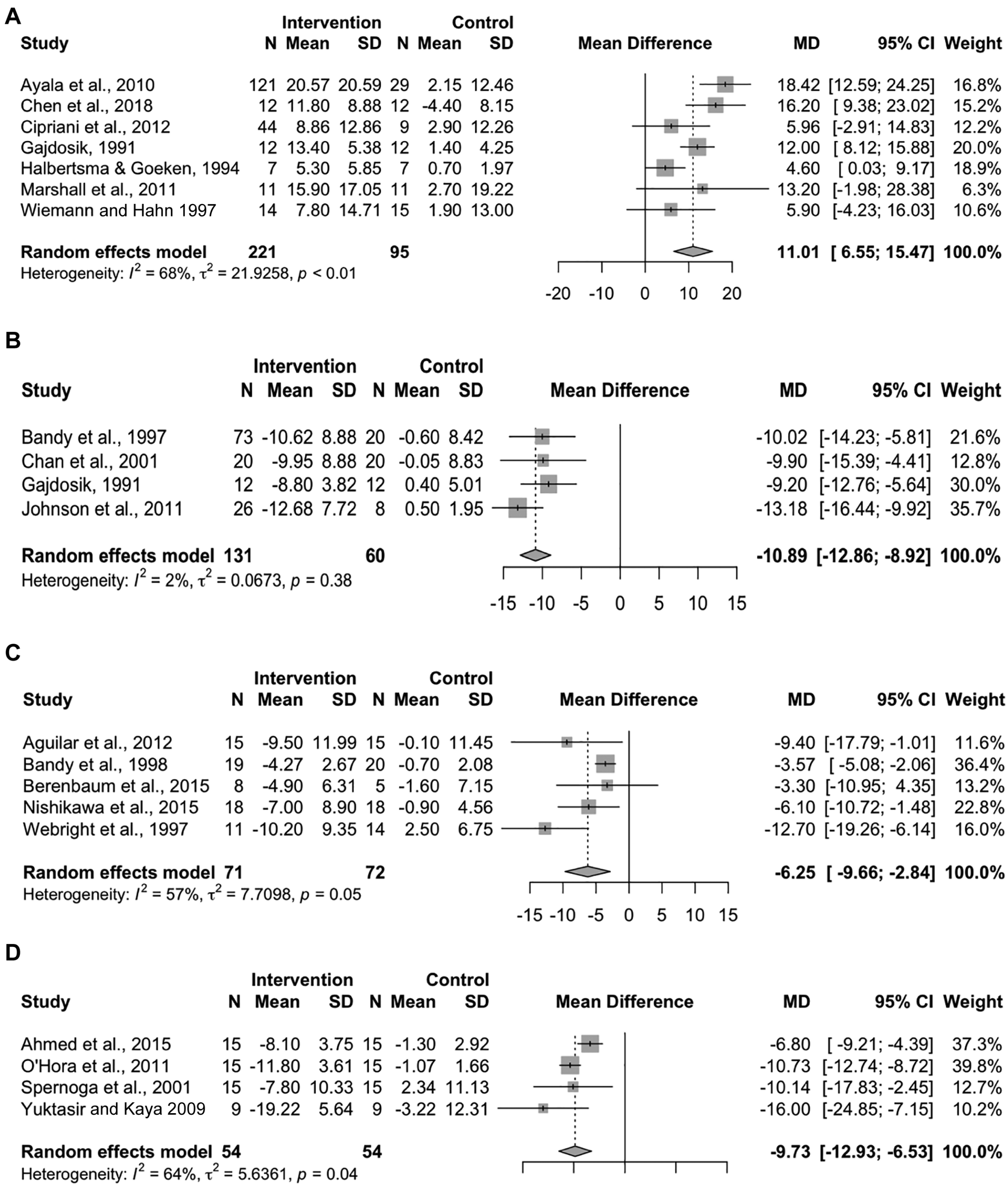

Figure 4. Factors affecting hamstring flexibility. Static stretching elicited improvement in (A) straight leg raise and (B) knee extension deficit. (C) Dynamic stretching and (D) proprioceptive neuromuscular facilitation also decreased knee extension deficit. MD, mean difference.

online). Athletes exercising with TheraBand resistance bands 4 times weekly experienced decreased between-limb hamstring peak torque differences, improving from 13.5 N·m to 4.9 N·m over 10 weeks.[5] Eccentric training was also effective, significantly reducing concentric strength asymmetry by 5.7%.[7] Asymmetry in eccentric strength improved by 4.3%; however, this did not achieve statistical significance.[131] Makaruk et al[78] compared static stretching and isometric strengthening techniques and determined that static stretching exhibited superior reductions in strength (4.2% vs 2.3%), H/Q ratio (1.8% vs 1.2%), and flexibility (3.2% vs 1.5%) differences between limbs.

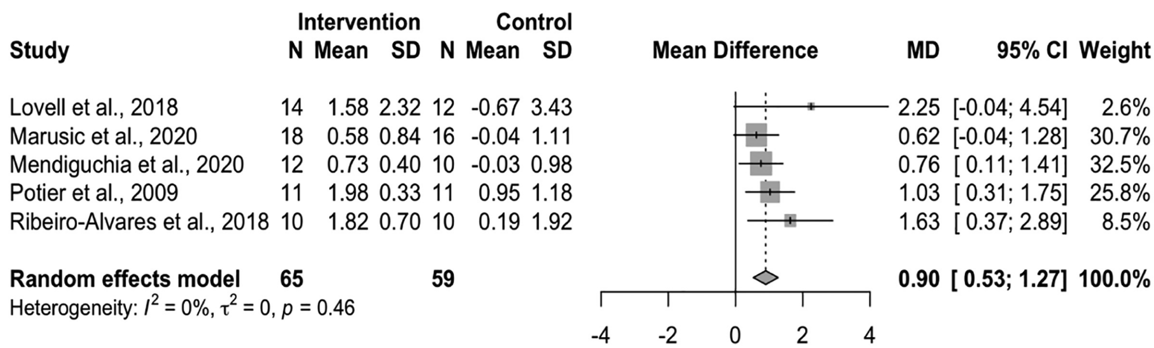

Figure 5. Effect of eccentric training on hamstring muscle fascicle length. MD, mean difference.

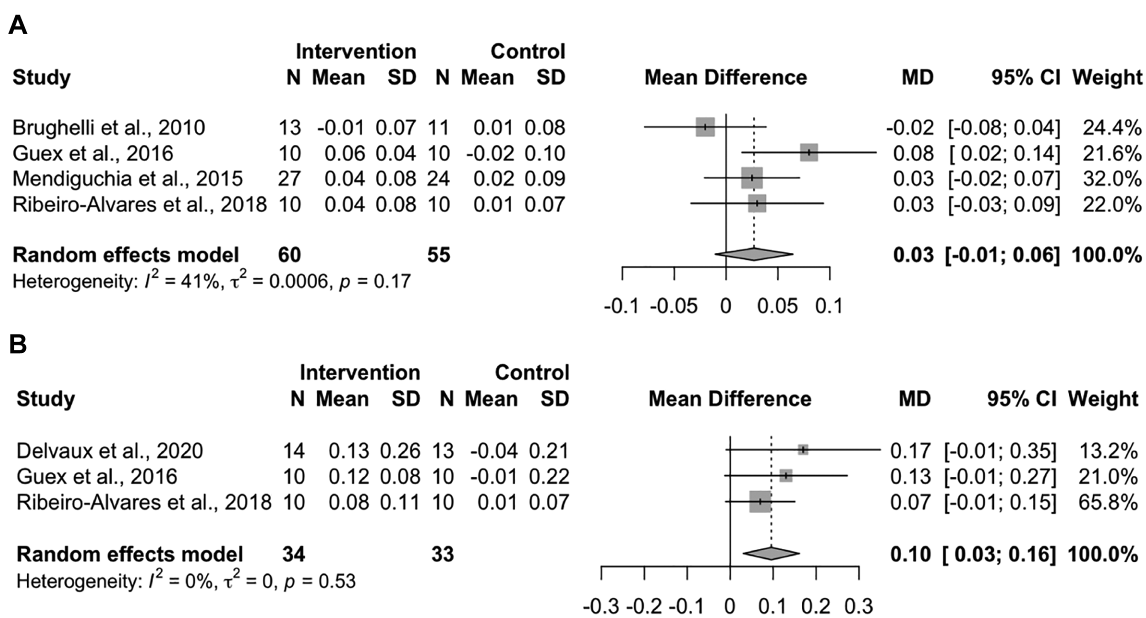

Figure 6. Effect of eccentric training on (A) conventional and (B) functional hamstring/quadriceps ratio. MD, mean difference.

DISCUSSION

Despite the devastating effect of hamstring injuries in sports, optimal methods of prevention have remained unclear. This systematic review and meta-analysis of 108 RCTs assessed the efficacy of various hamstring training programs by evaluating their effects on hamstring injury incidence and risk factors in athletes. The primary finding was that hamstring injury incidence decreased by as much as 70.0% with eccentric strengthening. In addition, several techniques successfully modified factors known to correlate with injury risk, including strength, flexibility, fascicle length, H/Q ratio, and limb asymmetry. Considering the prolonged recovery, high risk of recurrence, and potential financial and competitive implications associated with hamstring injury, these findings are critically important to athletes and those involved in their training.

Since previous studies have identified hamstring weakness and lack of flexibility as 2 of the most significant risk factors,[47,109] interventions aimed at increasing strength and range of motion have become integral components of contemporary prevention strategies. Strength consists of concentric and eccentric components, exemplifying a clinically and functionally important distinction, as each provides unique contributions to athletic activity. Specifically, concentric contraction underlies explosive movements,[110] while eccentric contraction modulates the terminal swing phase of the gait cycle, a period of substantial risk during high-speed running.[11] According to the literature, concentric strength improved with eccentric, concentric, blood flow–restricted, WBV, heavy back squat, FIFA 11+, and plyometric training methods, whereas eccentric strength benefited from eccentric, concentric, and plyometric training. Improvement in both types of strength after eccentric training supports this practice as a particularly efficient and effective method for reducing injury risk. In contrast, hamstring flexibility exhibited variable effects with eccentric training. Instead, static techniques produced the greatest increases in range of motion; however, the results disappeared within weeks of protocol completion and were counterbalanced by a potentially detrimental effect on hamstring strength. Persistent flexibility effects were obtained and strength deficits were avoided by PNF and dynamic stretching, although flexibility increased to a lesser degree than with static stretching. As such, both strength and flexibility goals must be defined by those considering stretching-based training to determine the optimal program.

In addition to intensive study of strength and flexibility, research of hamstring injury risk factors conducted over the past decade has expanded to evaluate several additional parameters. Muscle architecture is 1 such factor, as short fascicle length (<10.65 cm) has been associated with a 4-fold increase in injury risk compared with longer lengths.[23,124] Results indicate eccentric training increased fascicle length by an average of 0.9 cm, with Potier et al[107] reporting increases as large as 2.0 cm (33.6%) after a progressive protocol. Sprint training was also beneficial, whereas concentric training resulted in length reduction. Since the hamstring is responsible for modulating terminal stages of quadriceps-driven movements, a disproportionately low H/Q ratio presents another risk factor. According to the current meta-analyses, the conventional H/Q ratio was unchanged with eccentric training; however, the functional H/Q ratio demonstrated significant improvement. As the functional H/Q ratio characterizes muscle activity during leg deceleration, improvements translate to greater joint stability and reduced injury risk during high-speed running. Moreover, studies have investigated interventions aimed to reduce between-limb asymmetries, which have been reported to increase the likelihood of sustaining hamstring injury by 2.4 to 3.8.[24,36] This review determined that strength asymmetry was reduced with eccentric training, and imbalances in H/Q ratio and flexibility were normalized via resistance training and static stretching.

Overall, several interventions were effective in modifying risk factors associated with hamstring injury. Eccentric training represents a particularly successful injury prevention method, as demonstrated by its favorable effect on injury incidence and multiple risk factors. Other interventions such as plyometrics, PNF, WBV, and blood flow restriction were also beneficial for improving various risk factors. Still, hamstring injury rates have continued to increase.[46] A primary reason is poor implementation and adherence to prevention programs. This is remarkably apparent with eccentric strengthening protocols, and reports have identified associated muscle soreness as a significant barrier to participation.[23,91,131] In a study of 150 club-seasons across 50 European professional soccer teams, Bahr et al[16] reported complete participation in an eccentric training program in only 10.7% and partial participation in only 6.0% of seasons. Future studies are therefore needed to investigate the modification of prevention programs, particularly those incorporating eccentric strengthening, to optimize adherence and reduce rates of hamstring injury.

This study has several important limitations. First, the strength of any systematic review is dependent on the quality of evidence of included studies. Of the 108 RCTs included in this study, 19 raised some concerns and 7 were evaluated as high risk on the risk of bias assessment. This was principally attributable to inadequate randomization or missing outcome data. Moreover, blinding of participants was impossible in most studies because of the inability to introduce adequate placebo techniques. Although multiple databases were queried, the literature search included only studies published in English, potentially excluding relevant articles. Meta-analyses were performed when possible, but data pooling was restricted by differences in intervention protocols, patient populations, and outcome measures. This introduced heterogeneity and limited further comparison of prevention methods. Nevertheless, significant overall effects were observed in many instances. Finally, studies reporting outcomes of only compliant participants (ie, per protocol) were included, potentially resulting in overestimation of true effect. Barriers to compliance could not be assessed in this study. However, evaluation of outcomes in compliant athletes reflects the effect of hamstring training on injury prevention rather than effectiveness of intervention implementation as assessed by intention-to-treat analysis.

CONCLUSION

Several strategies exist to prevent hamstring injury and address known risk factors. Eccentric strengthening represents an efficient and effective method of reducing injury incidence while improving strength, fascicle length, H/Q ratio, and limb asymmetry. Limitations in flexibility are best addressed through stretching-based interventions. Moreover, plyometrics, PNF, WBV, and blood flow restriction were beneficial in addressing various risk factors. Taken together, the results of this systematic review and meta-analysis can assist athletes, trainers, coaches, and therapists in developing optimal hamstring training practices and preventing hamstring injuries.

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