

Title:

Hamstring strength and flexibility after hamstring strain injury: a systematic review and meta-analysis.

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Abstract:

Objective: To systematically review the evidence base related to hamstring strength and flexibility in previously injured hamstrings. Which variables, if any, should be monitored during hamstring rehabilitation?

Design: Systematic review and meta-analysis.

Data sources: A systematic literature search was conducted of PubMed, CINAHL, SPORTDiscus, Cochrane library, Web of Science, and EMBASE from inception to August 2015.

Inclusion Criteria: Full text English articles which included studies which assessed at least one measure of hamstring strength or flexibility in men and women with prior hamstring strain injury within 24 months of the testing date. Studies were required to have an uninjured comparison group (contralateral leg or uninjured control group).

Results: Twenty eight studies were included in the review, which in total included 898 participants. Previously injured legs demonstrated deficits across several variables. Lower isometric strength was found <7 days post injury (effect size, -1.72, 95%CI, -3.43 to 0.00), but this did not persist beyond 7 days after injury. The passive straight leg raise was restricted at multiple time points after injury (<10 days, effect size, -1.12, 95%CI, -1.76 to -0.48; 10-20 days, effect size, -0.74, 95%CI, -1.38 to -0.09; 20-30 days, effect size, -0.40, 95%CI, --0.78 to -0.03), but not at 40-50 days post injury. We report deficits that remained after return to play in isokinetically measured concentric (60°/sec , effect size, -0.33, 95%CI, -0.53 to -0.13) and Nordic eccentric knee flexor strength (effect size, -0.39, 95%CI, -0.77 to 0.00). The conventional hamstring to quadricep strength ratios were also reduced well after return to play (60:60°/sec , effect size, -0.32, 95%CI, -0.54 to -0.11; 240:240°/sec , effect size, -0.43, 95%CI, -0.83 to -0.03) and functional (30:240°/sec, effect size, -0.88, 95%CI, -1.27 to -0.48) but these effects were inconsistent across measurement velocities/method.

Conclusion: After hamstring strain, acute isometric and passive straight leg raise deficits resolve within 20-50 days. Deficits in eccentric and concentric strength and strength ratios persist after return to play, but this effect was inconsistent across measurement velocities/methods. Flexibility and isometric strength should be monitored throughout rehabilitation, but dynamic strength should be assessed at and following return to play.

What are the new findings:

After hamstring strain,

- Isometric strength returns to the level of the contralateral uninjured leg within 20 days
- Range of motion measured by the passive straight leg raise returns to the level of the contralateral uninjured leg within 50 days
- Lower dynamic strength (concentric, eccentric and associated strength ratios) in previous injured legs compared to the uninjured contralateral legs persist beyond return to play, , but this is inconsistent across measurement technique

How might it impact on clinical practice in the near future:

- Isometric strength and the passive straight leg raise provide a measure of progression during rehabilitation
- Dynamic strength (concentric/eccentric hamstrings strength and associated hamstring to quadriceps strength ratios) may also be helpful in monitoring progress through rehabilitation and return to play decisions
- This review adds weight to the argument that rehabilitation should continue after return to play if the goal is to achieve symmetry in strength and range of motion.

Introduction

Hamstring strain injuries (HSIs) are the most common non-contact injury in Australian rules football (1-5), soccer (6-10), rugby union (11-14), track and field (15-17) and American football (18). HSIs result in time away from competition (9), financial burden (9, 19) and impaired performance upon return to competition (20).

Further to this, recurrent hamstring strain often leads to a greater severity of injury than the initial insult (10, 14). The most commonly cited risk factor for future HSI is a previous HSI (21-24). The high recurrence rates of HSI (10, 14) are proposed to result from incomplete recovery and/or inadequate rehabilitation (25, 26) because of pressure for early return to play at the expense of convalescence (27). Consequently, there has been much interest recently in observations of hamstring structure and function in previously injured legs compared to control data (28-34). Despite the possible limitation of this approach, it is often agreed that deficits that exist in previously injured hamstrings could be a maladaptive response to injury. (35). As such, these deficits that persist beyond return to play could provide markers to better monitor athletes during and/or at the completion of rehabilitation (35).

Which parameters are the best markers to monitor an athlete's progress during rehabilitation? Conventional clinical practice focuses on measures of strength and flexibility, however the evidence is based on predominantly retrospective observations of strength (28, 29, 36-42), strength ratios (36, 37, 39, 40, 43, 44), and flexibility (26, 28, 42, 45-49) in previously injured athletes. These studies were limited in reporting single or isolated measures with methodologies and populations that differed from study to study. To advance knowledge, we aimed to systematically review the evidence base related to hamstring strength and flexibility in previously injured hamstrings.

Methods

Literature Search

A systematic literature search was conducted of PubMed, CINAHL, SPORTDiscus, Cochrane library, Web of Science, and EMBASE from inception to August 2015. Key words (Table 1) were chosen in accordance with the aims of the research. Retrieved references were imported into Endnote X7 (Thomson Reuters, New York, USA), with duplicates subsequently deleted. To ensure all recent and relevant references were retrieved, citation tracking was performed via Google Scholar and reference list searches were also conducted.

Table 1. Summary of keyword grouping employed during database searches.

Muscle Group	Injury	Time
Hamstring*	Injur*	Past
Semitendinosus	Strain*	Prior
Semimembranosus	Tear	Retrospective*
“Biceps Femoris”	Rupture*	Previous*
“Posterior Thigh”	Pull*	Recent*
Thigh	Trauma	Histor*
	Torn	

*truncation. Boolean term OR was used within categories, whilst AND was used between categories.

Selection Criteria

Selection criteria were developed prior to searching to maintain objectivity when identifying studies for inclusion. To address the aims, included papers had to:

- assess at least one parameter of hamstring strength (maximum strength, associated strength ratios and angle of peak torque) or flexibility in humans with a prior HSI within the prior 24 months of testing
- have control data for comparison, (whether it was a contralateral uninjured leg or an uninjured group) and
- have the full text journal article in English available (excluding reviews, conference abstracts, case studies/series)
- not include hamstring tendon or avulsion injuries as these are a different pathology

The titles and abstracts of each article were scanned by one author (NM) and removed if information was clearly inappropriate. Selection criteria were then independently applied to the remaining articles by three authors (NM, RT and DO). Full text was obtained for remaining articles, with selection criteria reapplied by one author (NM) and cross referenced by another author (DO).

Analysis

Assessing bias and methodological quality

Risk of bias assessment was performed independently by two examiners. We used a modified version of a checklist by Downs and Black (50). The original checklist contained 27 items, however many were relevant only to intervention studies. Since the majority of the papers in this review were of a retrospective nature, items 4, 8, 9, 13, 14, 15, 17, 19, 22, 23, 24, and 26 were excluded as they were not relevant to the aims of the review.

Of the remaining items, 1, 2, 3, 5, 6, 7, and 10 assessed factors regarding the reporting of aims, methods, data and results, whilst items 16, 18, 20, 21, and 25 assessed internal validity and bias. Item 27 was not suitable to the context of the current review, and was modified to address power calculations. Two new items (items 28 and 29) relating to injury diagnosis and rehabilitation/interventions were added to more appropriately assess the risk of bias and thus the modified checklist contained 17 items (Supplementary Table 1).

Fourteen of the items were scored 0 if the criterion was not met or it was unable to be determined, whilst successfully met criteria were scored 1 point. The other three items (items 5, 28 and 29) were scored 0, 1 or 2 points, as dictated by the criteria presented in Supplementary Table 1. This resulted in a total of 20 points available for each article.

Similarly modified versions of this checklist has been used in previous systematic reviews investigating factors leading to heel pain (51) and risk factors associated with hamstring injury (52). The risk of bias assessment was conducted by two authors (NM and DO), with results expressed as a percentage. In the case of disagreement between assessors, an independent individual was consulted with consensus reached via discussion if necessary. In situations where one of the assessors (DO) was a listed author on a study included for review, the independent individual completed the risk of bias assessment in their place.

Data Extraction

Relevant data was extracted including the participant numbers, population and sampling details, diagnosis technique, severity of injury, time from injury to testing (in days assuming 30.4 days per month, 365 days per year), variables investigated and how these were tested, results including statistical analysis, and, where appropriate, potential confounders that may affect strength or flexibility outcomes. The major confounders include other lower limb injuries likely to affect strength and flexibility, interventions and rehabilitation programs

performed. Furthermore, insufficient evidence exist regarding the interaction between gender and HSI, thus mixed gender cohorts were considered as a potential confounder.

Data Analysis

Although objectively synthesizing evidence via a meta-analysis is often desirable, this technique was not able to be applied to the all the evidence retrieved in this review, due to insufficient reporting of data (i.e. two or more studies or subgroups with mean, standard deviation, and participant numbers for contralateral leg comparisons) or methodological variations between studies.

When sufficient data was available, meta-analysis and graphical outputs were performed using selected packages (53-55) on R (56). Standardised mean differences (Cohen's d) facilitated the comparison of studies reporting variables in different units, with effect estimates and 95% confidence intervals summarised in forest plots. A random effects model was used to determine the overall effect estimate of all studies within the variable or subgroup as appropriate, with variance estimated through a restricted maximum likelihood (REML) method. The magnitude of the effect size were interpreted as small ($d = 0.20$), moderate ($d = 0.50$) and large ($d = 0.80$) according to thresholds proposed by Cohen (57), Where studies reported multiple types of data (e.g. multiple isokinetic velocities, multiple subgroups or multiple time points), these data were analysed as subgroups to avoid biasing the weighting of the data. These time bands were dictated by the data available. Where data were available in the acute stages (prior to return to play), time bands were kept at less than 10 days as it would be expected that deficits would change relatively rapidly during this time, due to on-going rehabilitation and recovery.

Data presented for participants at or after return to play were pooled for two reasons, 1) no included study reported any on-going rehabilitation after return to play and 2) many of these studies had variable time from injury until testing between individual participants. Where a study had multiple time-points that fit within post return to play time-band (e.g. at return to play and follow-up), the earlier option was chosen as there was expected to be a lower chance of bias due to other uncontrolled or unmonitored activities. For the purposes of meta-regression (employed to assess the effects of time since injury), studies with multiple time points were pooled to provide the best assessment of the effect of time on the given variable. Therefore, each subgroup/time point was considered as a unique study, allowing sufficient data (>10 subgroups) for meta-regression analysis (58) providing that time from injury until testing was reported. Funnel plots were visually inspected for asymmetry to

assess publication bias. Heterogeneity was determined by the I^2 statistic, and can be interpreted via the following thresholds (58):

- 0-40%: might not be important
- 30-60%: may represent moderate heterogeneity
- 50-90%: may represent substantial heterogeneity
- 75-100%: considerable heterogeneity

In situations where it was deemed that reported data (i.e. mean, standard deviation, participant numbers for contralateral leg comparisons) was insufficient for meta-analysis and could not be obtained via supplementary material or from contacting the corresponding author, a best evidence synthesis (59) was employed. The level of evidence was ranked according to criteria consistent with previously published systematic reviews (60, 61) as outlined below:

- Strong: two or more studies of a high quality and generally consistent findings ($\geq 75\%$ of studies showing consistent results)
- Moderate: one high quality study and/or two or more low quality studies and generally consistent findings ($\geq 75\%$ of studies showing consistent results),
- Limited: one low quality study,
- Conflicting: inconsistent findings ($< 75\%$ of studies showing consistent results),
- None: no supportive findings in the literature

A high quality study was defined as a risk of bias assessment score of $\geq 70\%$ whereas a low quality study had a risk of bias assessment score $< 70\%$ (58)

Results

Search results

The search strategy consisted of six steps (Figure 1). The initial search yielded 7805 items (Cochrane library = 131; Pubmed = 2407, CINAHL = 604; SportDISCUS = 640; Web of Science = 1049; EMBASE = 2974) from all databases. After duplicates were removed, 4306 items remained. Title and abstract screening resulted in 92 remaining articles, reference list hand searching and citation tracking resulted in the addition of 7 articles. Independent application of the selection criteria yielded 28 articles to be included in the review, 23 of which were included in meta-analysis.

Figure 1 approximately here

Risk of bias Assessment

Risk of bias assessment of each article is displayed in Table 2. It is important to note that the risk of bias assessment was not the basis of exclusion. Included articles ranged from a score of 8 to 18 of a possible 20(40% – 90%).

Description of studies

Participants

A sample of 898 participants ($n = 802$ male, $n = 96$ female; age range, 15-47 years) were examined across the included studies. Seventeen studies included only male participants (29, 34, 36, 37, 39-43, 45, 46, 48, 49, 62-65), ten studies had mixed gender (26, 28, 33, 47, 66-71), whilst only one exclusively studied females (72). Participants were generally considered recreationally active at a minimum.

Injury

Methods of diagnosis varied between studies, with some studies using multiple methods of diagnosis. Twelve studies used clinical criteria (26, 28, 33, 34, 36, 37, 42, 48, 67-70), ten used magnetic resonance imaging (MRI) (26, 28, 29, 33, 34, 63, 66, 68-70), five had medical or health practitioner diagnosis (39, 41, 43, 48), seven used a questionnaire or self-report (40, 46, 47, 49, 59, 64, 72), two used ultrasound (36, 37), and two had unclear methods of diagnosis (45, 71). Description of severity of injury varied significantly between studies, with the most common being time to return to play (26, 28, 29, 40, 42, 43, 48, 49, 64, 68) and grade (I-III) of injury (29, 31, 33, 39, 63, 67, 69-71). Description of time from injury to testing varied significantly between studies (range, 2-690 days).

Outcomes

The strength variables examined were concentric, eccentric and isometric (absolute and normalised to body mass), strength ratios (usually hamstring to quadriceps (H:Q)), and angle of peak torque. The five flexibility variables examined were passive straight leg raise, active straight leg raise, passive knee extension, active knee extension and the sit and reach. All five strength variables (concentric, eccentric, isometric, strength ratios, angle of peak torque) and three flexibility variables (passive straight leg raise, active knee extension, passive knee extension) were included for meta-analysis. Sufficient data were available to run meta-regression analysis for isometric strength, the passive straight leg raise and the passive knee extension. The best evidence synthesis method was applied to remaining variables for

295 Table 2. Itemised scoring of study quality using a modified (Supplementary Table 1) Downs and Black checklist (50).

First author, year	1	2	3	5	6	7	10	11	12	16	18	20	21	25	27	28	29	Total	%	Quality
Arumugam 2015	0	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	10	50	Low
Askling 2006	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	2	1	14	70	High
Askling 2010	1	1	1	1	1	1	0	0	0	1	1	1	1	0	0	2	0	12	60	Low
Brockett 2004	1	1	1	1	1	0	1	0	0	1	1	1	1	0	0	1	1	12	60	Low
Croisier 2000	1	1	1	1	1	1	0	0	0	1	1	1	0	1	0	1	0	11	55	Low
Croisier 2002	1	1	1	1	1	1	0	0	0	1	0	1	1	1	0	2	0	12	60	Low
Dauty 2003	1	1	0	1	1	1	0	0	0	1	1	1	1	1	0	1	0	11	55	Low
Doherty 2012	1	1	1	1	0	1	1	0	0	1	1	1	1	1	0	0	0	11	55	Low
Hennessy 1993	1	1	0	0	1	1	0	0	0	1	1	1	1	0	0	0	0	8	40	Low
Jonhagen 1994	1	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0	0	12	60	Low
Lee 2009	1	1	1	1	1	1	1	0	0	1	1	0	1	1	0	1	0	12	60	Low
Lowther 2012	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	11	55	Low
Mackay 2010	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	11	55	Low
Opar 2013a	1	1	0	1	1	1	1	0	0	1	1	1	1	1	0	2	0	13	65	Low
Opar 2013b	1	1	1	2	1	1	1	0	0	1	1	1	1	1	0	1	1	15	75	High
Opar 2015	1	1	1	2	1	1	1	0	0	1	1	1	1	1	1	2	0	16	80	High
O'Sullivan & Burns 2009	1	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0	0	12	60	Low
O'Sullivan 2009	1	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0	0	12	60	Low
O'Sullivan 2008	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	0	0	11	55	Low
Reurink 2015	1	1	1	2	1	1	1	0	0	1	1	1	1	1	1	2	2	18	90	High
Reurink 2013	1	1	1	2	1	1	1	0	0	1	1	1	1	1	1	2	2	18	90	High
Sanfilippo 2013	1	1	1	2	1	1	1	0	0	1	1	1	1	1	0	2	2	17	85	High
Silder 2010	1	1	1	1	1	1	1	0	0	1	1	1	0	1	0	2	1	14	70	High
Silder 2013	1	1	1	2	1	1	1	0	0	1	1	1	1	1	0	2	2	17	85	High
Sole 2011	1	1	1	1	1	1	1	0	0	1	1	1	0	1	0	1	0	12	60	Low
Timmins 2015	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	2	1	16	80	High
Tol 2014	1	1	0	1	1	1	1	0	0	1	1	1	1	1	0	2	2	15	75	High
Worrell 1991	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	0	0	11	55	Low

296 A high quality study was defined as a risk of bias assessment score of $\geq 70\%$ whereas a low quality study had a risk of bias assessment score $< 70\%$

which insufficient data were available for meta-analysis. The best evidence synthesis is summarised in Table 3.

Strength

Concentric Strength

Data for all studies which examined concentric strength can be found in Supplementary Table 2.

Meta-analysis. Concentric strength was measured isokinetically at 60 (29, 40, 48, 62-64, 67, 68, 72), 180 (29, 40, 62, 72) and 300°/sec (39, 40, 63, 72). A statistically significant small effect for lower concentric strength at 60°/sec was found in previously injured legs (effect size, -0.33; 95%CI, -0.53 to -0.13; I^2 , 0%), but no significant effects were found at 180 or 300°/sec (Figure 2).

Best evidence synthesis. Of the dynamic strength variables which were not included in the meta-analysis, one (seated isokinetic at 240°/sec) (36, 37, 68) had moderate evidence for a decrease in strength in the previously injured hamstrings. Concentric strength at 270°/sec in a seated position (42) had limited evidence and concentric strength at 60°/sec in a prone position (49) had no supporting evidence.

***Figure 2 approximately ***

Eccentric strength

Data for all studies which examined eccentric strength can be found in Supplementary Table 3.

Meta-analysis. Eccentric strength measured during the Nordic hamstring exercise (34, 41, 65) and isokinetically at 60 (29, 48, 63, 64, 71) and 180°/sec (29, 71) were included in the meta-analysis. Significant deficits in previously injured legs were found for eccentric strength measured via the Nordic hamstring exercise (effect size, -0.39; 95%CI, -0.77 to 0.00; I^2 , 0%), but no other method (Figure 3).

Best evidence synthesis. Eccentric isokinetic strength measured at 30 (36, 37, 42, 62) and 120°/sec (36, 37) had moderate evidence, indicating lower strength in previously injured hamstrings, whereas measures at 230 (42) and 300°/sec (39) had limited evidence. The measurement of eccentric strength at 60°/sec in a prone position (49) had no supporting evidence.

330 Table 3. Best evidence synthesis data for all major categories of outcome variables assessed in individuals with a prior hamstring strain injury.

Variable	Testing method	No. of studies	Consistency (%)			Quality (mean \pm SD)	Level of evidence of difference
			Decrease	No change	Increase		
Concentric strength*	Seated isokinetic (240°/sec)	3	100	0	0	67 \pm 16	Moderate
Eccentric strength	Seated isokinetic (30°/sec)	4	75	25	0	58 \pm 3	Moderate
Eccentric strength	Seated isokinetic (120°/sec)	2	100	0	0	58 \pm 4	Moderate
Isometric Strength [#]	Hip, 0°; knee, 90°	1	100	0	0	90	Moderate
Concentric strength	Seated isokinetic (270°/sec)	1	100	0	0	60	Limited
Eccentric strength	Seated isokinetic (230°/sec)	1	100	0	0	60	Limited
Eccentric strength	Seated isokinetic (300°/sec)	1	100	0	0	60	Limited
Eccentric Hamstring:Hip flexor peak torque ratio	Seated/standing isokinetic (300°/sec)	1	100	0	0	60	Limited
Eccentric angle of peak torque	Seated isokinetic (30°/sec)	1	0	0	100	55	Limited
Flexibility [¥]	Passive knee extension	3	67	33	0	57 \pm 3	Conflicting
Flexibility	Active straight leg raise	2	50	50	0	50 \pm 14	Conflicting

331 Consistency refers to the percentage of studies showing a particular outcome; *, one study (65) showed deficit present at return to play and 6-
332 months post injury; ¥, deficit assessed post return to play; #, deficit present at initial evaluation and 7-day follow-up.

333

***Figure 3 approximately ***

Isometric Strength

Data for all studies which examined isometric strength can be found in Supplementary Table 4.

Meta-analysis. Isometric strength measured at long muscle lengths (hip, 0°; knee, 0-15°) was included in the meta-analysis (28, 34, 69). Measures were taken at multiple time-points (<7 days, 7-14, 21, 42, and >180 days) post injury, thus subgroups were analysed (Figure 4) and meta regression was performed. A large effect for lower long-length isometric strength was statistically significant in previously injured legs compared to the uninjured contralateral legs less than seven days post injury (effect size, -1.72; 95%CI, -3.43 to 0.00; I^2 , 91%), but not at any other time point. Meta-regression analysis (Figure 5) revealed no significant effect for time since injury for isometric strength (intercept, -0.92, $p = 0.002$; coefficient, 0.003, $p = 0.292$).

Best evidence synthesis. One study (69) assessed isometric strength in a short muscle length (hip 0°, knee 90°). This study did not statistically test for differences between muscles, but based on effect size and confidence intervals, isometric strength was reduced at the initial evaluation (effect size, -0.74; 95%CI, -1.07 to -0.41), and at the 7 day follow-up (effect size, -0.39; 95%CI, -0.71 to -0.07) but not the 26 week follow-up (effect size, -0.12; 95%CI, -0.45 to 0.20).

***Figure 4 approximately ***

***Figure 5 approximately ***

Hamstring:Quadricep Torque Ratio

Data for all studies which examined H:Q ratios can be found in Supplementary Table 5 & 6.

Meta-analysis. The conventional H:Q ratio, whereby peak torque of each muscle group is assessed during concentric isokinetic contraction at 60:60 (36, 37, 40, 43, 48, 62, 71, 72), 180:180 (40, 62, 71, 72), 240:240 (36, 37), and 300:300°/sec (39, 40, 72) (Figure 6). A statistically significant small effect for a lower conventional H:Q ratio was found in previously injured legs compared to the uninjured contralateral legs at 60:60 (effect size, -0.32; 95%CI, -0.54 to -0.11; $I^2 = 0\%$) and 240:240°/sec (effect size, -0.43; 95%CI, -0.83 to -

0.03; I^2 , 0%), but not 180:180 and 300:300°/sec. Meta-analysis of the functional H:Q (fH:Q), whereby the hamstring group is assessed eccentrically, but the quadriceps groups is assessed concentrically, included isokinetic velocities 30:240 (36, 37, 68) and 60:60°/sec (43, 48, 64, 71) (Figure 7). A large effect was found for a lower ratio was found in previously injured legs at 30:240°/sec (effect size, -0.88; 95%CI, -1.27 to -0.48; I^2 , 0%), but no significant differences between injured and uninjured legs at 60:60°/sec.

Best evidence synthesis. One study which examined H:Q (60:60°/sec) (49) was not included in the meta-analysis due to the prone and supine position in which knee flexor and quadriceps strength were assessed respectively. This study found no significant difference between injured and uninjured legs. No supporting evidence was found for the fH:Q strength ratio at 180:180 (71), 30:60, 30:180°/sec (62) and limited evidence found for 300:300°/sec (39). The eccentric H:Q, whereby both knee flexor and quadriceps strength is assessed via eccentric contractions was assessed isokinetically in prone/supine (49) position. Neither study found any differences between previously injured and uninjured legs. Limited evidence was found for eccentric knee flexor torque to concentric hip flexor torque ratio deficits in previously injured legs (effect size, -0.9) compared to uninjured contralateral legs (39).

***Figure 6 approximately ***

***Figure 7 approximately ***

Angle of peak torque

Data for all studies which examined optimal angle of peak torque can be found in Supplementary Table 7.

Meta-analysis. The optimal angle of peak torque (concentric 60°/sec) had sufficient data (62, 67, 68) for meta-analysis. No significant differences between injured or uninjured legs were found (Figure 8).

Best evidence synthesis. Limited evidence was found for the eccentric angle of peak torque to occur at significantly shorter muscle lengths in the injured legs compared to the uninjured contralateral legs at 30°/sec (62). No differences were found for angle of peak torque between legs/groups at 240 (68) and 300°/sec (39) concentrically or 300°/sec (39) eccentrically measured angle of peak torque.

***Figure 8 approximately ***

Flexibility

Passive straight leg raise

Data for all studies which examined the passive straight leg raise can be found in Supplementary Table 8.

Meta-analysis. Quantitative analysis of the passive straight leg raise (26, 28, 63, 69) revealed significantly reduced range of motion in previously injured legs compared to the uninjured contralateral leg. A large effect was found within 10 days (effect size, -1.12; 95%CI, -1.76 to -0.48; I^2 , 81%), a moderate effect between 10-20 days (effect size, -0.74; 95%CI, -1.38 to -0.09; I^2 , 76%), and a small effect between 20-30 days (effect size, -0.40; 95%CI, -0.78 to -0.03; I^2 , 4%) since the time of injury, with no significant effect found at 40 days or more since the time of injury (Figure 9). Meta-regression analysis (Figure 10) revealed a significant effect for time since injury (intercept, -0.81, $p < 0.0001$; coefficient, 0.006, $p = 0.019$), indicating that the magnitude of the range of motion deficit decreases with increasing time from injury.

***Figure 9 approximately ***

***Figure 10 approximately ***

Passive knee extension

Data for all studies which examined the passive knee extension can be found in Supplementary Table 9.

Meta-analysis. No significant differences were found for the passive knee extension measure at either time-point subgroup analysed (<10 days and 20-30 days post injury; Figure 11a,b).

Best evidence synthesis. A subset of the passive knee extension (insufficient data for subgroup meta-analysis, unable to be pooled with acute data) showed conflicting evidence across the three studies (46, 47, 49) that conducted this assessment post return to play.

Active knee extension

Data for all studies which examined the active knee extension can be found in Supplementary Table 9.

Meta-analysis. No significant differences were found for the passive knee extension measure at either time-point subgroup analysed (<10 days, 10-30 days, and >180 days post injury; Figure 11c,d,e).

***Figure 11 approximately ***

Active straight leg raise

Data for all studies which examined the active straight leg raise can be found in Supplementary Table 8.

Best evidence synthesis. Conflicting evidence was found for deficits in the active straight leg raise (45, 66). Of note, the one study (66) which did find deficits in previously injured legs performed the active straight leg raise in a rapid manner (Askling-H test) and as such this study could not be appropriately pooled with the other data for meta-analysis purposes.

Sit and reach

Best evidence synthesis. No evidence for differences in the sit and reach were found between healthy and previously injured participants (48, 64).

Discussion

Our systematic review revealed that after hamstring strain, isometric strength and passive straight leg raise deficits normalised within 20-50 days. Deficits at or after return to play, if they did exist, manifested during dynamic strength measures (eccentric and concentric strength and their associated H:Qstrength ratios).

We only included research articles that contained data from participants who had previously sustained a HSI (between 2 and 690 days prior). As a result, we cannot determine whether the reported deficits were the cause of injury or the result of injury. Given the increased risk of future HSI in those with an injury history (21-24), the characteristics that exist in these legs should be given consideration by the clinicians responsible for rehabilitation and clearance to return to play.

Strength and flexibility deficits after hamstring injury

Conventional rehabilitation practice traditionally focuses on restoring isometric strength and range of motion (73). The meta-analysis revealed that deficits in long length (hip, 0°; knee, 0-15°) isometric strength and the passive straight leg raise are resolved 20-50 days post injury. This provides support for the use of the passive straight leg raise and isometric strength measures during rehabilitation (73). Furthermore, deficits in isometric strength and range of motion (as measured by the active knee extension test) just after return to play are

independent predictors of re-injury (74), suggesting that these variables likely also have value in criteria based rehabilitation progressions. However, where evidence of deficits were found beyond return to play, these were during measures of dynamic strength.

The evidence supporting deficits in eccentric strength in those with prior HSI is mixed (29, 34, 36, 37, 39, 41-43, 48, 64, 65, 71). Lower levels of eccentric hamstring strength are proposed to increase the likelihood that the demands of high force musculotendinous lengthening, such as during the terminal swing phase of running, exceeds the mechanical limits of the tissue (75). It may be that lower eccentric strength in previously injured hamstrings is at least partly responsible for the greater risk of recurrent hamstring strain. (76).

Other measures of dynamic strength, including concentric strength (29, 33, 36, 37, 40, 48, 62-64, 67, 68, 72) and both conventional (33, 36, 37, 39, 40, 43, 48, 62, 67, 71, 72) and functional (36, 37, 39, 43, 48, 62, 64, 68, 71) H:Q strength ratios also show conflicting findings, with measures at some testing velocities showing lower strength in previously injured legs, but others showing no differences. The reasons for these discrepancies are unclear, but may be due to inherent differences in groups studied, and/or methodological issues. For example, studies which included females tended to observe slightly higher strength in previously injured legs (71, 72). Insufficient data was available to assess this observation via regression analysis, thus more research is needed to investigate any potential gender-specific responses to HSI. The particulars of the rehabilitation performed could also explain disparate, as differing rehabilitation strategies would result in differing adaptations. Rehabilitation was rarely controlled in the included studies, suggesting more studies should aim to control rehabilitation to limit this potential confounder.

Mechanisms that may explain long-term dynamic muscle strength deficits

There is the possibility that chronic deficits in dynamic strength in previously hamstring-strain injured legs is a downstream outcome of prolonged neuromuscular inhibition (35). Reduced activation of previously injured hamstrings has been associated with maximal eccentric contractions (29, 30, 48, 77), particularly at long muscle lengths (29, 48). What remains to be seen, however, is whether or not these deficits are associated with increased risk of injury or re-injury, and what the most appropriate intervention is to ameliorate these deficits. However, activation deficits do not occur during concentric contractions (29, 48),

thus further research is needed to understand why dynamic strength deficits tend to persist beyond return to play.

Clinical implications

The data presented in this review have implications for practitioners who are required to rehabilitate and return athletes to play following HSIs. The supplementary results tables provide practitioners a detailed resource of data for almost all strength and flexibility measures that have been assessed in athletes with a prior HSI. These data can be used to compare individual athlete/patient data. It should also enable practitioners to select measures to monitor in their injured athletes which are known to be in deficit despite ‘successful’ return to play. The presented evidence justifies the use of the passive straight leg raise and isometric strength measures to monitor progression through rehabilitation, whilst additional measures of dynamic strength may have more value at and after return to play.

In addition, the present review would also question the use of commonly recommended (75, 78) and employed markers for successful rehabilitation, such as knee flexor angle of peak torque. The use of angle of peak knee flexor torque, particularly during concentric contraction, in athletes with prior HSI has been popularised following the seminal paper (67), however, the ensuing evidence is generally conflicting (33, 39, 62, 68) suggesting that the value of this measure should be questioned.

Limitations

The primary limitation of this review is that the retrospective nature of the data makes it impossible to determine if deficits are the cause or result of injury. For example, eccentric strength deficits could be the result of uncorrected strength deficiency that may have caused injury, as higher levels of eccentric strength and eccentric training are associated with a reduction in new and recurrent HSI (74, 79, 80). Furthermore, the majority of the included studies did not control rehabilitation, and this introduces another potential source of bias. For example, a study in which participants focused heavily on eccentric exercise as part of rehabilitation may show no evidence of significant eccentric strength deficits post HSI. Consequently, the effect of these interventions on strength and flexibility outcomes remains an area for future research. Ideally, researchers should control rehabilitation to minimise confounding, and where this is not possible, collect and report details of rehabilitation protocols. Inconsistent time from injury until testing between studies also introduces bias. We analysed data in time-bands and performed meta-regression analysis where possible to assess and adjust for this potential confounder, but also acknowledge that this approach was

limited by within study variability, variability between studies within the time-band subgroups, and insufficient data for regression analysis. Future research should investigate the effect of time since injury on deficits, particularly prior to return to play, as strength and flexibility appear to change rapidly during this period.

One of the difficulties of this review was the numerous methods employed by different studies to assess a given parameter. For strength testing, it appeared that lower isokinetic velocities ($\leq 60^\circ/\text{sec}$) were the most sensitive to deficits, however there is insufficient data at higher velocities to draw definitive conclusions. Similarly, a number of different measures of flexibility (passive (26, 28, 42, 66) and active (45, 66) straight leg raise, passive (26, 46, 47, 49) and active knee extension (26, 48), sit and reach test (48)) have been assessed in previously injured athletes, with inconsistent findings amongst studies. Indeed, within each variable, the meta-analysis revealed significant heterogeneity as determined by the I^2 statistic in certain measures, particularly in the initial days following injury.

To address these issues as far as possible, we performed sensitivity analysis (Supplementary Table 10) to examine the influence of individual studies on effect estimates and heterogeneity where moderate ($\geq 30\%$) heterogeneity (58) may have been present. Whilst high heterogeneity often impairs the validity of synthesised data, the low number of studies in many of these subgroups precludes confidence in the precision in these I^2 estimates, suggesting more studies are needed to properly interpret heterogeneity estimates. These studies should also take care to accurately describe diagnostic procedures, injury severity and other lower limb injuries likely to confound results. The data reported in this review may also have limited application to female athletes, as majority of the data was obtained from male only or predominately male cohorts. We acknowledge that the search strategy may not have captured all relevant literature. However, reference list searching and citation tracking was also performed to enhance article retrieval.

Conclusion

In conclusion, the meta-analysis found that deficits in isometric strength and flexibility (as measured by the passive straight leg raise) resolve within 20-50 days following HSI. Deficits that were present beyond return to play were found for dynamic measures of strength (concentric and eccentric strength, and conventional and functional H:Q strength ratios). This evidence suggests that clinicians monitor isometric strength and the passive straight leg raise throughout rehabilitation, whilst dynamic measures of strength may hold more value at/after

568 return to play. Furthermore, it may behove clinicians and patients to continue rehabilitation
569 after return to play.

References

1. Gabbe B, Finch C, Wajswelner H, et al. Australian football: injury profile at the community level. 2002;5(2):149-60.
2. Orchard J, Seward H. Epidemiology of injuries in the Australian Football League, seasons 1997–2000. *British Journal of Sports Medicine*. 2002;36(1):39-44.
3. Orchard J, Seward H. Injury report 2009: Australian football league. *Sport Health*. 2010;28(2):10.
4. Orchard J, Seward H. Injury Report 2008: Australian Football League. *Sport Health*. 2009;27(2):29.
5. Seward H, Orchard J, Hazard H, et al. Football injuries in Australia at the elite level. *The Medical Journal of Australia*. 1993;159(5):298-301.
6. Ekstrand J, Gillquist J. Soccer injuries and their mechanisms: a prospective study. *Medicine and Science in Sports and Exercise*. 1983;15(3):267-70.
7. Ekstrand J, Hägglund M, Waldén M. Injury incidence and injury patterns in professional football: the UEFA injury study. *British Journal of Sports Medicine*. 2009;bjsports60582.
8. Hawkins R, Hulse M, Wilkinson C, et al. The association football medical research programme: an audit of injuries in professional football. *British Journal of Sports Medicine*. 2001;35(1):43-7.
9. Woods C, Hawkins R, Hulse M, et al. The Football Association Medical Research Programme: an audit of injuries in professional football—analysis of preseason injuries. *British Journal of Sports Medicine*. 2002;36(6):436-41.
10. Woods C, Hawkins R, Maltby S, et al. The Football Association Medical Research Programme: an audit of injuries in professional football—analysis of hamstring injuries. *British Journal of Sports Medicine*. 2004;38(1):36-41.
11. Brooks JH, Fuller C, Kemp S, et al. Epidemiology of injuries in English professional rugby union: part 1 match injuries. *British Journal of Sports Medicine*. 2005;39(10):757-66.
12. Brooks JH, Fuller C, Kemp S, et al. Epidemiology of injuries in English professional rugby union: part 2 training Injuries. *British Journal of Sports Medicine*. 2005;39(10):767-75.
13. Brooks JH, Fuller C, Kemp S, et al. A prospective study of injuries and training amongst the England 2003 Rugby World Cup squad. *British journal of Sports Medicine*. 2005;39(5):288-93.
14. Brooks JH, Fuller CW, Kemp SP, et al. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *The American Journal of Sports Medicine*. 2006;34(8):1297-306.
15. Sugiura Y, Saito T, Sakuraba K, et al. Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *Journal of Orthopaedic & Sports Physical Therapy*. 2008;38(8):457-64.
16. Yeung SS, Suen AM, Yeung EW. A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor. *British Journal of Sports Medicine*. 2009;43(8):589-94.
17. Bennell KL, Crossley K. Musculoskeletal injuries in track and field: incidence, distribution and risk factors. *Australian Journal of Science and Medicine in Sport*. 1996;28(3):69-75.
18. Feeley BT, Kennelly S, Barnes RP, et al. Epidemiology of National Football League training camp injuries from 1998 to 2007. *The American Journal of Sports Medicine*. 2008;36(8):1597-603.

19. Hickey J, Shield AJ, Williams MD, et al. The financial cost of hamstring strain injuries in the Australian Football League. *British Journal of Sports Medicine*. 2014;48(8):729-30.
20. Verrall GM, Kalairajah Y, Slavotinek JP, et al. Assessment of player performance following return to sport after hamstring muscle strain injury. *Journal of science and medicine in sport / Sports Medicine Australia*. 2006;9(1-2):87-90.
21. Arnason A, Sigurdsson SB, Gudmundsson A, et al. Risk factors for injuries in football. *The American Journal of Sports Medicine*. 2004;32(1 Suppl):5s-16s.
22. Orchard JW. Intrinsic and Extrinsic Risk Factors for Muscle Strains in Australian Football Neither the author nor the related institution has received any financial benefit from research in this study. *The American Journal of Sports Medicine*. 2001;29(3):300-3.
23. Hägglund M, Waldén M, Ekstrand J. Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons. *British Journal of Sports Medicine*. 2006;40(9):767-72.
24. Verrall GM, Slavotinek JP, Barnes PG, et al. Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. *British Journal of Sports Medicine*. 2001;35(6):435-9; discussion 40.
25. Connell DA, Schneider-Kolsky ME, Hoving JL, et al. Longitudinal study comparing sonographic and MRI assessments of acute and healing hamstring injuries. *American Journal of Roentgenology*. 2004;183(4):975-84.
26. Silder AMY, Sherry MA, Sanfilippo J, et al. Clinical and Morphological Changes Following 2 Rehabilitation Programs for Acute Hamstring Strain Injuries: A Randomized Clinical Trial. *The Journal of Orthopaedic and Sports Physical Therapy*. 2013;43(5):284-99.
27. Orchard J, Best TM. The management of muscle strain injuries: an early return versus the risk of recurrence. *Clinical Journal of Sport Medicine*. 2002;12(1):3-5.
28. Askling C, Saartok T, Thorstensson A. Type of acute hamstring strain affects flexibility, strength, and time to return to pre-injury level. *British Journal of Sports Medicine*. 2006;40(1):40-4.
29. Opar DA, Williams MD, Timmins RG, et al. Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. *Journal of Electromyography and Kinesiology*. 2013;23(3):696-703.
30. Opar DA, Williams MD, Timmins RG, et al. Rate of torque and electromyographic development during anticipated eccentric contraction is lower in previously strained hamstrings. *The American Journal of Sports Medicine*. 2013;41(1):116-25.
31. Silder A, Heiderscheit BC, Thelen DG, et al. MR observations of long-term musculotendon remodeling following a hamstring strain injury. *Skeletal Radiology*. 2008;37(12):1101-9.
32. Silder A, Reeder SB, Thelen DG. The influence of prior hamstring injury on lengthening muscle tissue mechanics. *Journal of Biomechanics*. 2010;43(12):2254-60.
33. Silder A, Thelen DG, Heiderscheit BC. Effects of prior hamstring strain injury on strength, flexibility, and running mechanics. *Clinical Biomechanics (Bristol, Avon)*. 2010;25(7):681-6.
34. Timmins RG, Shield AJ, Williams MD, et al. Biceps Femoris Long Head Architecture: A Reliability and Retrospective Injury Study. *Medicine & Science in Sports & Exercise*. 2015;47(5):905-13.
35. Fyfe JJ, Opar DA, Williams MD, et al. The role of neuromuscular inhibition in hamstring strain injury recurrence. *Journal of Electromyography and Kinesiology*. 2013;23(3):523-30.
36. Croisier JL, Crielaard JM. Hamstring muscle tear with recurrent complaints: An isokinetic profile. *Isokinetics and Exercise Science*. 2000;8(3):175-80.

37. Croisier JL, Forthomme B, Namurois MH, et al. Hamstring muscle strain recurrence and strength performance disorders. *The American Journal of Sports Medicine*. 2002;30(2):199-203.
38. Freckleton G, Cook J, Pizzari T. The predictive validity of a single leg bridge test for hamstring injuries in Australian Rules Football Players. *British Journal of Sports Medicine*. 2013.
39. Lee MJ, Reid SL, Elliott BC, et al. Running biomechanics and lower limb strength associated with prior hamstring injury. *Medicine and Science in Sports and Exercise*. 2009;41(10):1942-51.
40. O'Sullivan K, O'Ceallaigh B, O'Connell K, et al. The relationship between previous hamstring injury and the concentric isokinetic knee muscle strength of Irish Gaelic footballers. *BMC Musculoskeletal Disorders*. 2008;9:30.
41. Opar DA, Piatkowski T, Williams MD, et al. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *The Journal of Orthopaedic and Sports Physical Therapy*. 2013;43(9):636-40.
42. Jonhagen S, Nemeth G, Eriksson E. Hamstring injuries in sprinters. The role of concentric and eccentric hamstring muscle strength and flexibility. *The American Journal of Sports Medicine*. 1994;22(2):262-6.
43. Dauty M, Potiron-Josse M, Rochcongar P. Identification of previous hamstring muscle injury by isokinetic concentric and eccentric torque measurement in elite soccer player. *Isokinetics and Exercise Science*. 2003;11(3):139-44.
44. Houweling TAW, Head A, Hamzeh MA. Validity of isokinetic testing for previous hamstring injury detection in soccer players. *Isokinetics and Exercise Science*. 2009;17(4):213-20.
45. Hennessey L, Watson AW. Flexibility and posture assessment in relation to hamstring injury. *British Journal of Sports Medicine*. 1993;27(4):243-6.
46. Lowther D, O'Connor A, Clifford AM, et al. The relationship between lower limb flexibility and hamstring injury in male Gaelic footballers. *Physiotherapy Ireland*. 2012;33(1):22-8.
47. O'Sullivan K, Murray E, Sainsbury D. The effect of warm-up, static stretching and dynamic stretching on hamstring flexibility in previously injured subjects. *BMC Musculoskeletal Disorders*. 2009;10:37.
48. Sole G, Milosavljevic S, Nicholson HD, et al. Selective strength loss and decreased muscle activity in hamstring injury. *The Journal of Orthopaedic and Sports Physical Therapy*. 2011;41(5):354-63.
49. Worrell TW, Perrin DH, Gansneder BM, et al. Comparison of isokinetic strength and flexibility measures between hamstring injured and noninjured athletes. *The Journal of Orthopaedic and Sports Physical Therapy*. 1991;13(3):118-25.
50. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *Journal of Epidemiology and Community Health*. 1998;52(6):377-84.
51. Irving DB, Cook JL, Menz HB. Factors associated with chronic plantar heel pain: a systematic review. *Journal of Science and Medicine in Sport / Sports Medicine Australia*. 2006;9(1-2):11-22; discussion 3-4.
52. Freckleton G, Pizzari T. Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. *British Journal of Sports Medicine*. 2013;47(6):351-8.
53. Schwarzer G. meta: General Package for Meta-Analysis. 2015.
54. Viechtbauer W. Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*. 2010;36(3):1-48.

55. Wickham H. *ggplot2: elegant graphics for data analysis*: Springer Science & Business Media; 2009.
56. R Development Core Team. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing; 2010.
57. Cohen J. A power primer. *Psychological bulletin*. 1992;112(1):155.
58. Higgins J, Green S. *Cochrane Handbook for Systematic Reviews of Interventions* Version 5.1.0 [updated March 2011]. The Cochrane Collaboration. 2011.
59. Slavin RE. Best evidence synthesis: An intelligent alternative to meta-analysis. *Journal of Clinical Epidemiology*. 1995;48(1):9-18.
60. de Visser HM, Reijman M, Heijboer MP, et al. Risk factors of recurrent hamstring injuries: a systematic review. *British Journal of Sports Medicine*. 2012;46(2):124-30.
61. Serner A, van Eijck CH, Beumer BR, et al. Study quality on groin injury management remains low: a systematic review on treatment of groin pain in athletes. *British Journal of Sports Medicine*. 2015.
62. Mackey C, O'Sullivan K, O'Connor A, et al. Altered hamstring strength profile in Gaelic footballers with a previous hamstring injury. *Isokinetics and Exercise Science*. 2011;19(1):47-54.
63. Tol JL, Hamilton B, Eirale C, et al. At return to play following hamstring injury the majority of professional football players have residual isokinetic deficits. *British Journal of Sports Medicine*. 2014;48(18):1364-9.
64. Arumugam A, Milosavljevic S, Woodley S, et al. Effects of external pelvic compression on isokinetic strength of the thigh muscles in sportsmen with and without hamstring injuries. *Journal of Science and Medicine in Sport*. 2015;18(3):283-8.
65. Opar DA, Williams MD, Timmins RG, et al. The Effect of Previous Hamstring Strain Injuries on the Change in Eccentric Hamstring Strength During Preseason Training in Elite Australian Footballers. *American Journal of Sports Medicine*. 2015;43(2):377-84.
66. Askling CM, Nilsson J, Thorstensson A. A new hamstring test to complement the common clinical examination before return to sport after injury. *Knee surgery, Sports Traumatology, Arthroscopy*. 2010;18(12):1798-803.
67. Brockett CL, Morgan DL, Proske U. Predicting Hamstring Injury in Elite Athletes. *Medicine and Science in Sports and Exercise*. 2004;36(3):379-87.
68. Sanfilippo J, Silder A, Sherry MA, et al. Hamstring Strength and Morphology Progression after Return to Sport from Injury. *Medicine and Science in Sports and Exercise*. 2013;45(3):448-54.
69. Reurink G, Goudswaard GJ, Moen MH, et al. Rationale, secondary outcome scores and 1-year follow-up of a randomised trial of platelet-rich plasma injections in acute hamstring muscle injury: the Dutch Hamstring Injection Therapy study. *British Journal of Sports Medicine*. 2015.
70. Reurink G, Goudswaard GJ, Oomen HG, et al. Reliability of the active and passive knee extension test in acute hamstring injuries. *The American Journal of Sports Medicine*. 2013;41(8):1757-61.
71. Doherty J, Van Lunen BL, Ismaeli ZC, et al. Hamstring Strength Measurements in Collegiate Athletes With a History of Hamstring Injury. *Athletic Training & Sports Health Care: The Journal for the Practicing Clinician*. 2012;4(1):38-44.
72. O'Sullivan K, Burns S. Comparing concentric isokinetic thigh muscle strength in female gaelic football players with and without previous hamstring injury. *Physiotherapy Ireland*. 2009;30(1):39-44.
73. Heiderscheit BC, Sherry MA, Silder A, et al. Hamstring Strain Injuries: Recommendations for Diagnosis, Rehabilitation and Injury Prevention. *The Journal of Orthopaedic and Sports Physical Therapy*. 2010;40(2):67-81.

74. De Vos R-J, Reurink G, Goudswaard G-J, et al. Clinical findings just after return to play predict hamstring re-injury, but baseline MRI findings do not. *British Journal of Sports Medicine*. 2014;48(18):1377-84.
75. Croisier JL. Factors associated with recurrent hamstring injuries. *Sports Medicine (Auckland, NZ)*. 2004;34(10):681-95.
76. Opar DA, Williams MD, Timmins RG, et al. Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise*. 2015;47(4):857-65.
77. Bourne MN, Opar DA, Williams MD, et al. Muscle activation patterns in the Nordic hamstring exercise: Impact of prior strain injury. *Scandinavian Journal of Medicine & Science in sports*. 2015.
78. Mendiguchia J, Brughelli M. A return-to-sport algorithm for acute hamstring injuries. *Physical Therapy in Sport*. 2011;12(1):2-14.
79. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian Journal of Medicine & Science in Sports*. 2003;13(4):244-50.
80. Petersen J, Thorborg K, Nielsen MB, et al. Preventive Effect of Eccentric Training on Acute Hamstring Injuries in Men's Soccer A Cluster-Randomized Controlled Trial. *The American Journal of Sports Medicine*. 2011;39(11):2296-303.

Contributorship:

NM conducted the search, risk of bias and criteria assessments, extracted the data, performed all analysis and drafted the manuscript. AS and MW contributed to interpretation of results and the manuscript. RT conducted criteria assessments and contributed to the manuscript. DO conducted risk of bias and criteria assessments and contributed to the interpretation of results and the manuscript.

Competing interests:

Dr David Opar and Dr Anthony Shield are listed as co-inventors on an international patent application filed for the experimental device (PCT/AU2012/001041.2012) used in three of the included studies in this review. The authors declare no other competing interests.

Figures

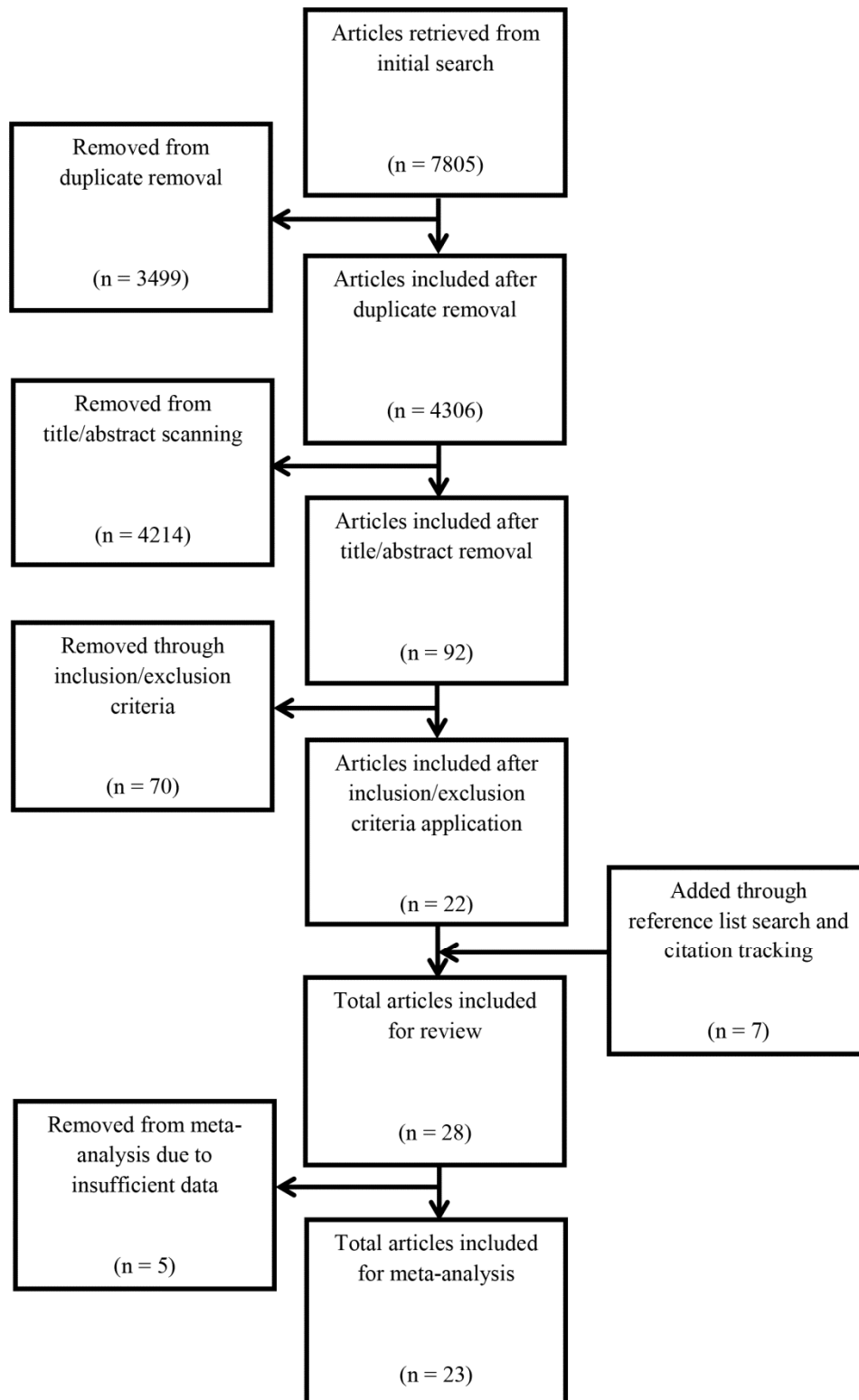


Figure 1. Flow diagram outlining steps for study inclusion/exclusion.

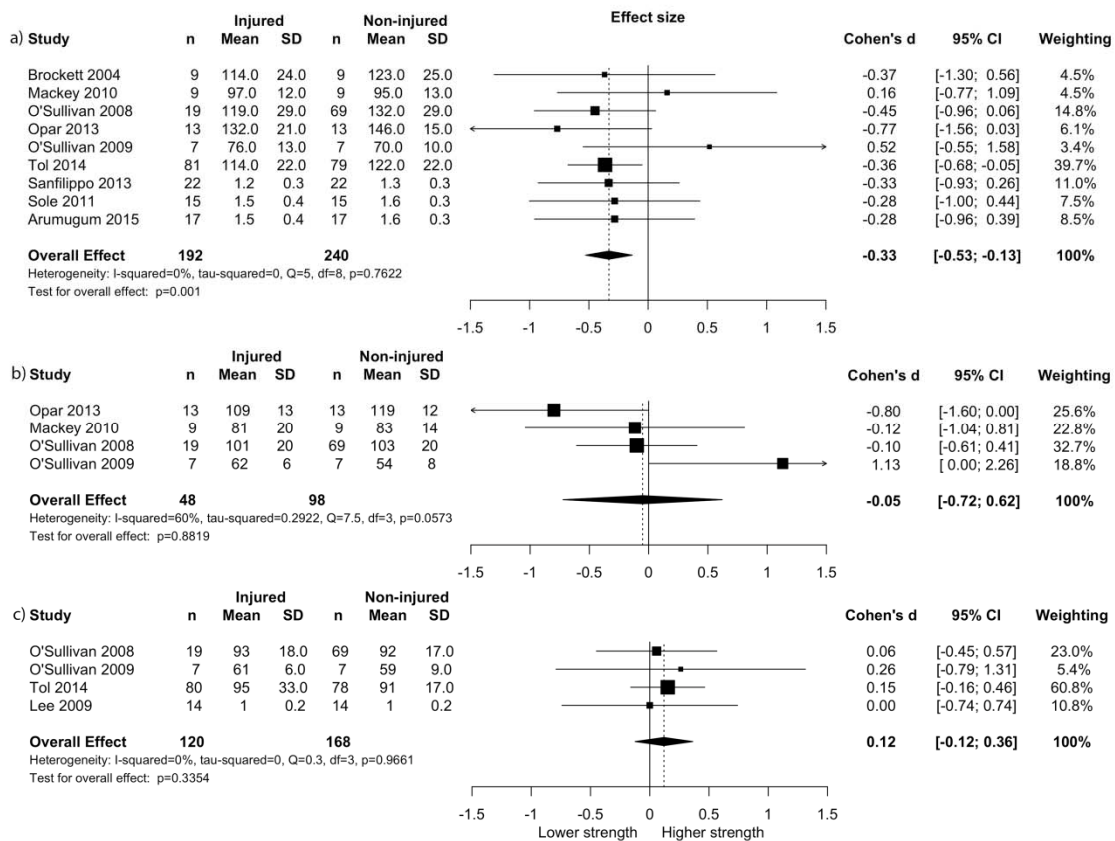


Figure 2. Forest plot of concentric strength measured at a) 60°/sec, b) 180°/sec, and c) 300°/sec

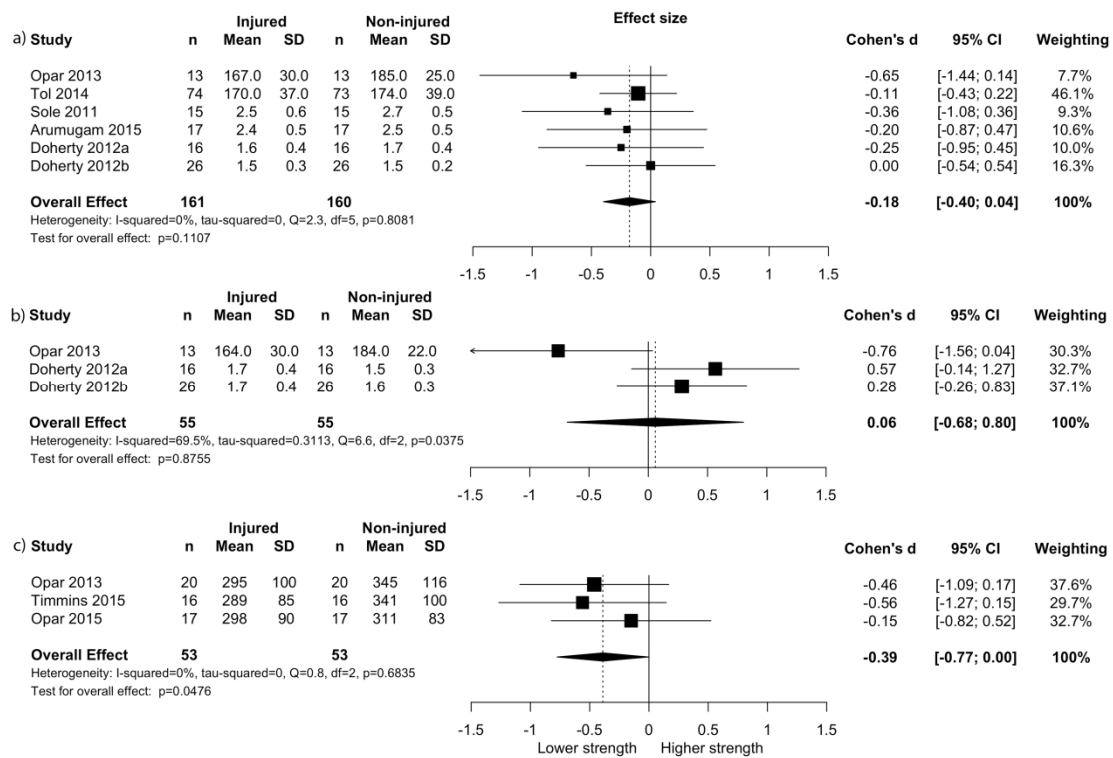


Figure 3. Forest plot of eccentric strength measured at a) 60°/sec, b) 180°/sec, and c) during the Nordic hamstring exercise. Note that one study (68) had two subgroups, a, Division III athletes; b, Division I athletes.

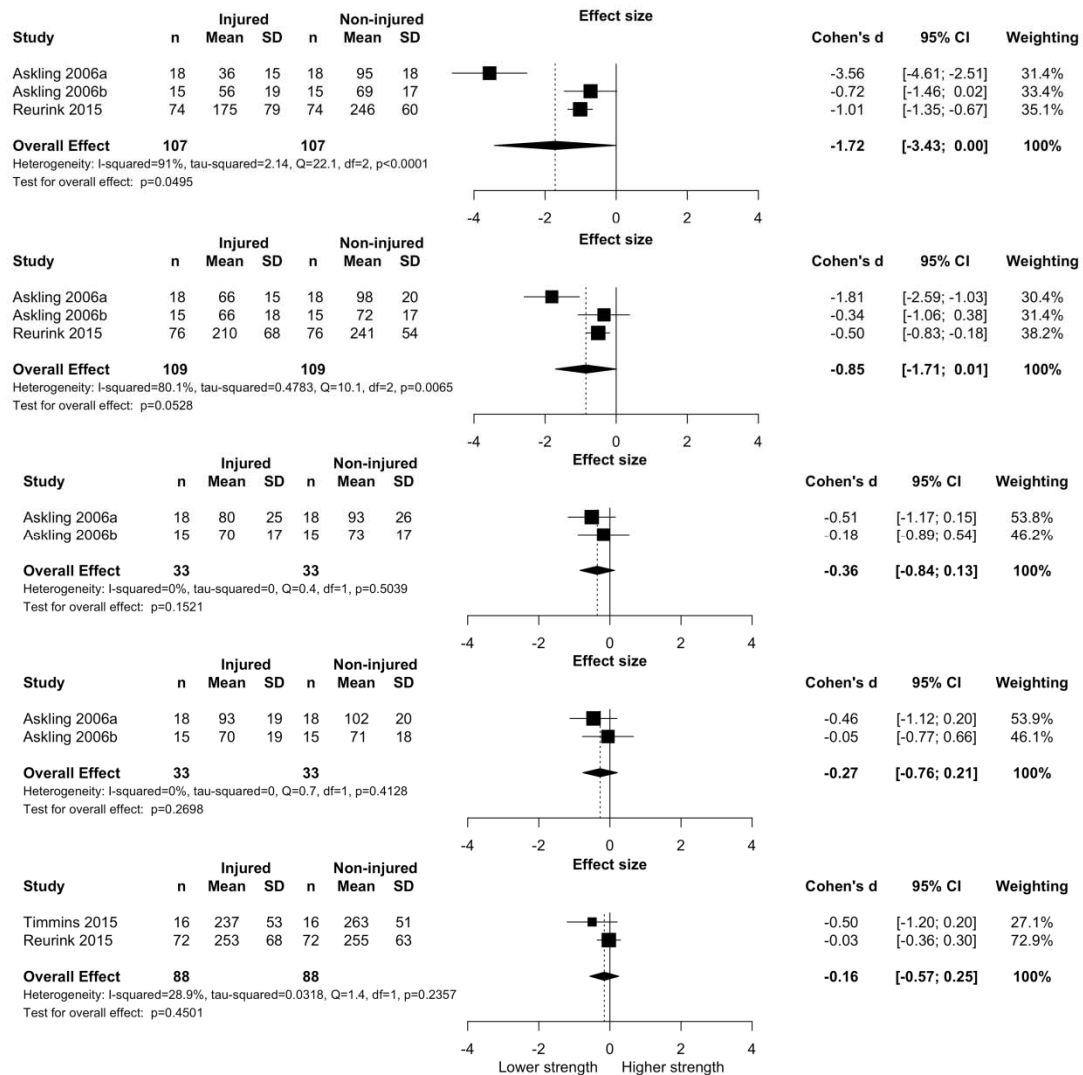


Figure 4. Forest plot of isometric strength assessed at a) <3 days post injury, b) 10 days post injury, c) 21 days post injury, d) 42 days post injury and e) >180 days post injury

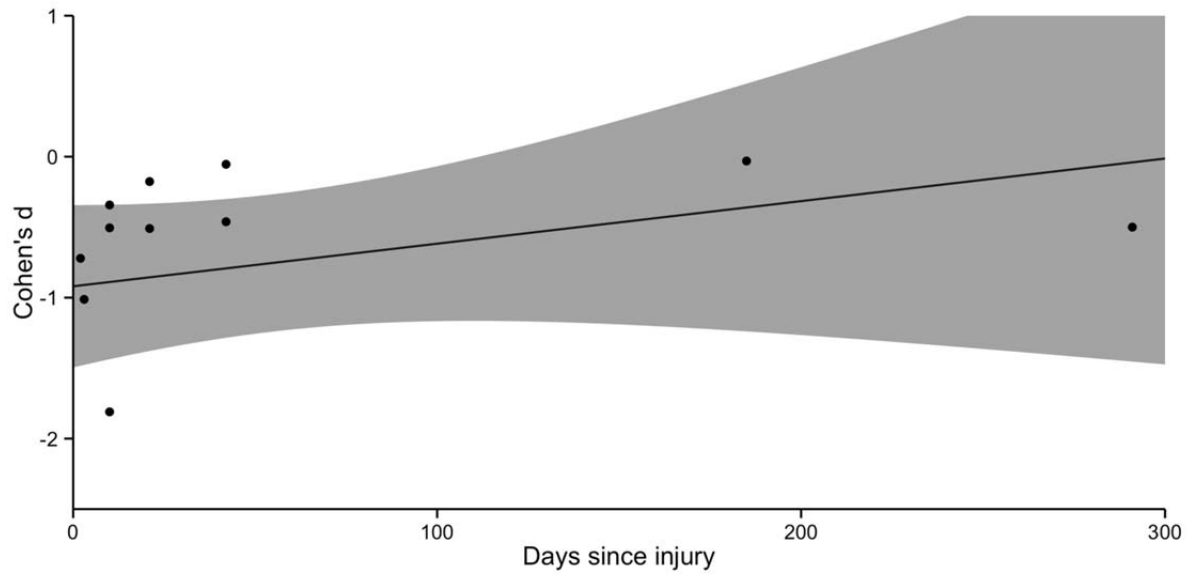


Figure 5. Meta-regression plot (with 95%CI) for isometric strength. Intercept, -0.92, $p = 0.002$; coefficient, 0.003, $p = 0.292$.

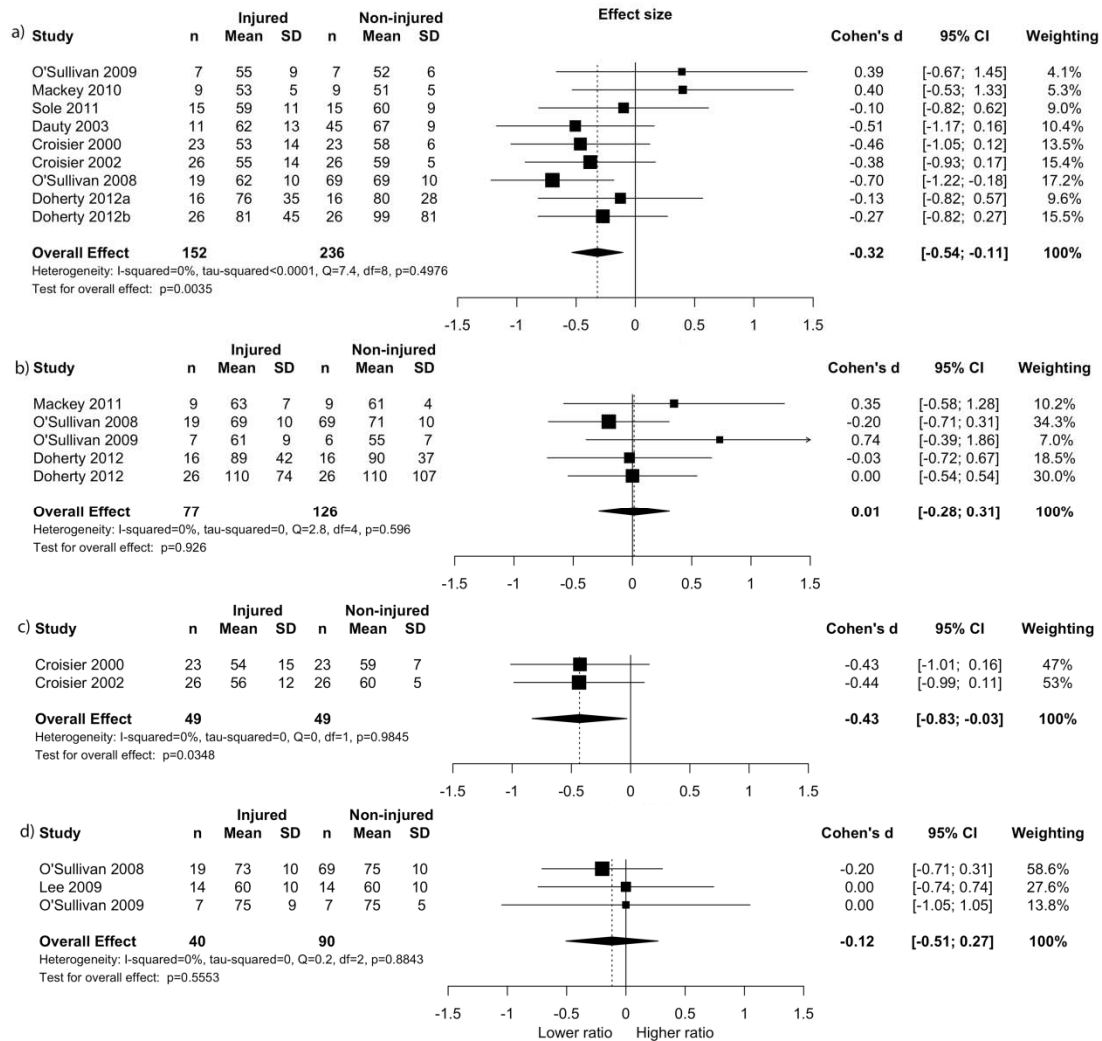


Figure 6. Forest plot of conventional H:Q ratio assessed at a) 60:60°/sec, b) 180:180°/sec, c) 240:240°/sec, and d) 300:300°/sec. Note that one study (68) had two subgroups, a, Division III athletes; b, Division I athletes.

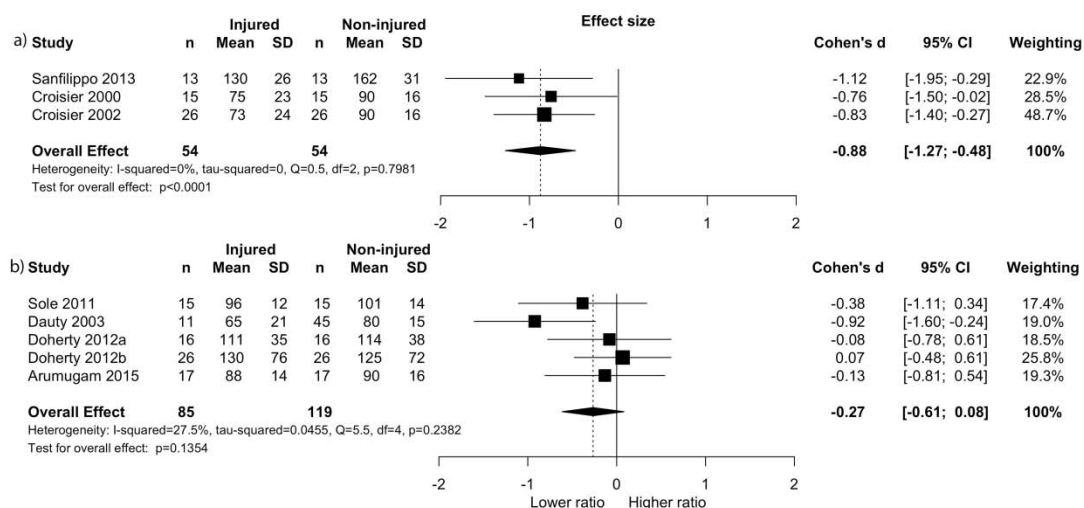


Figure 7. Forest plot of the fH:Q ratio assessed at a) 30:240°/sec and b) 60:60°/sec. Note that one study (68) had two subgroups, a, Division III athletes; b, Division I athletes.

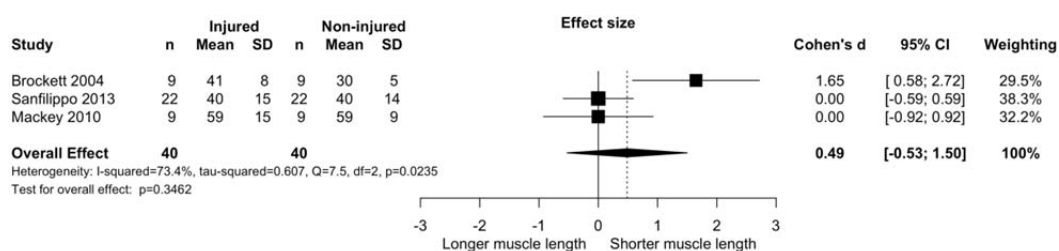


Figure 8. Forest plot for angle of peak torque assessed during 60°/sec concentric contraction

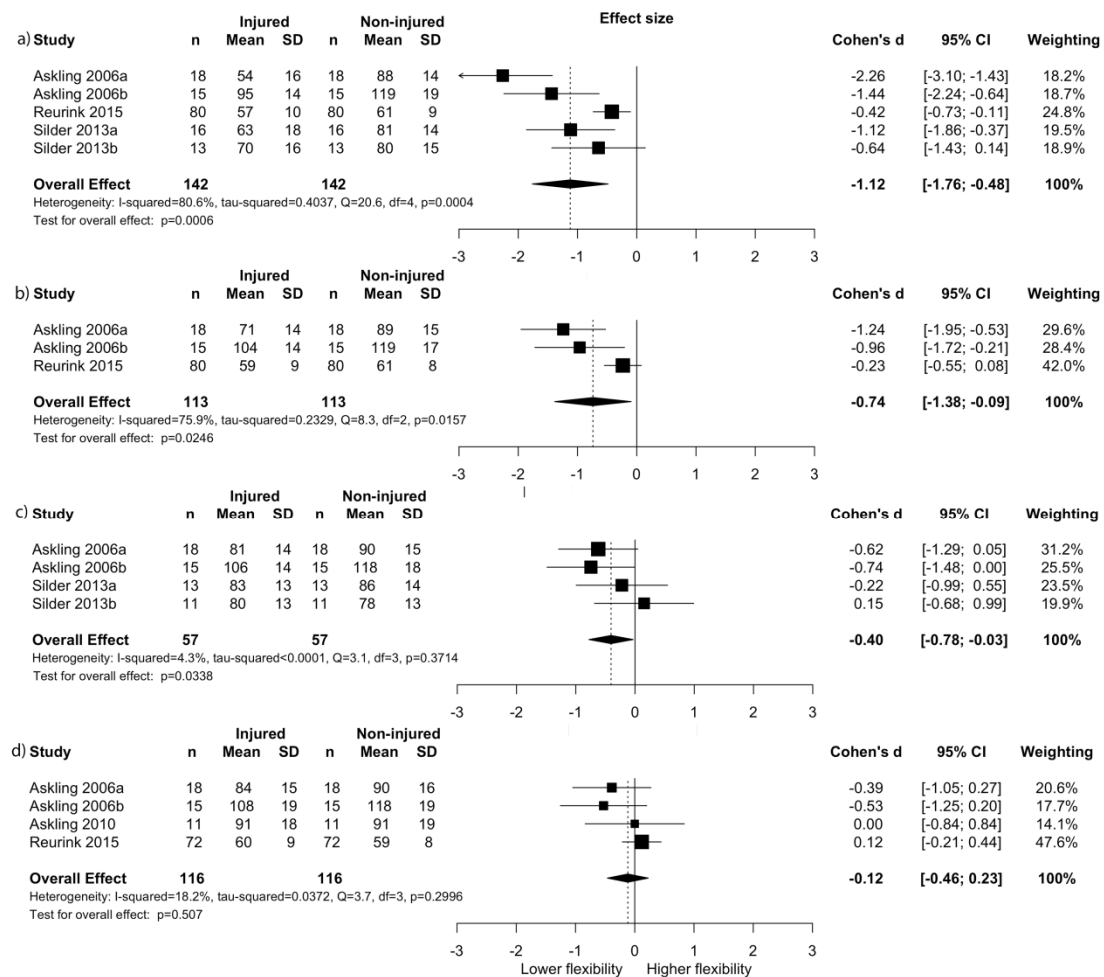


Figure 9. Forest plot of the passive straight leg raise at a) <10 days post injury, b) 10 days post injury, c) 21-30 days post injury, and d) >40 days post injury. Note that one study (26) had two subgroups, a, Progressive agility and trunk stabilisation rehabilitation protocol (PATs); b, Progressive running and eccentric strengthening rehabilitation protocol (PRES).

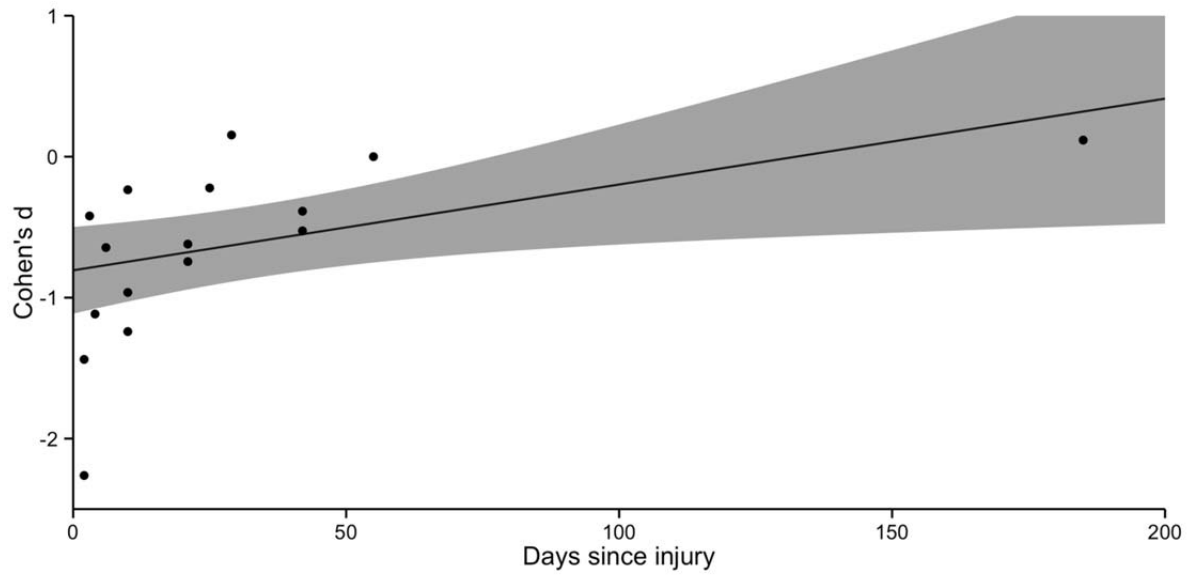


Figure 10. Meta-regression plot (with 95%CI) for the passive straight leg raise. Intercept, -0.81, $p < 0.0001$; coefficient, 0.006, $p = 0.019$.

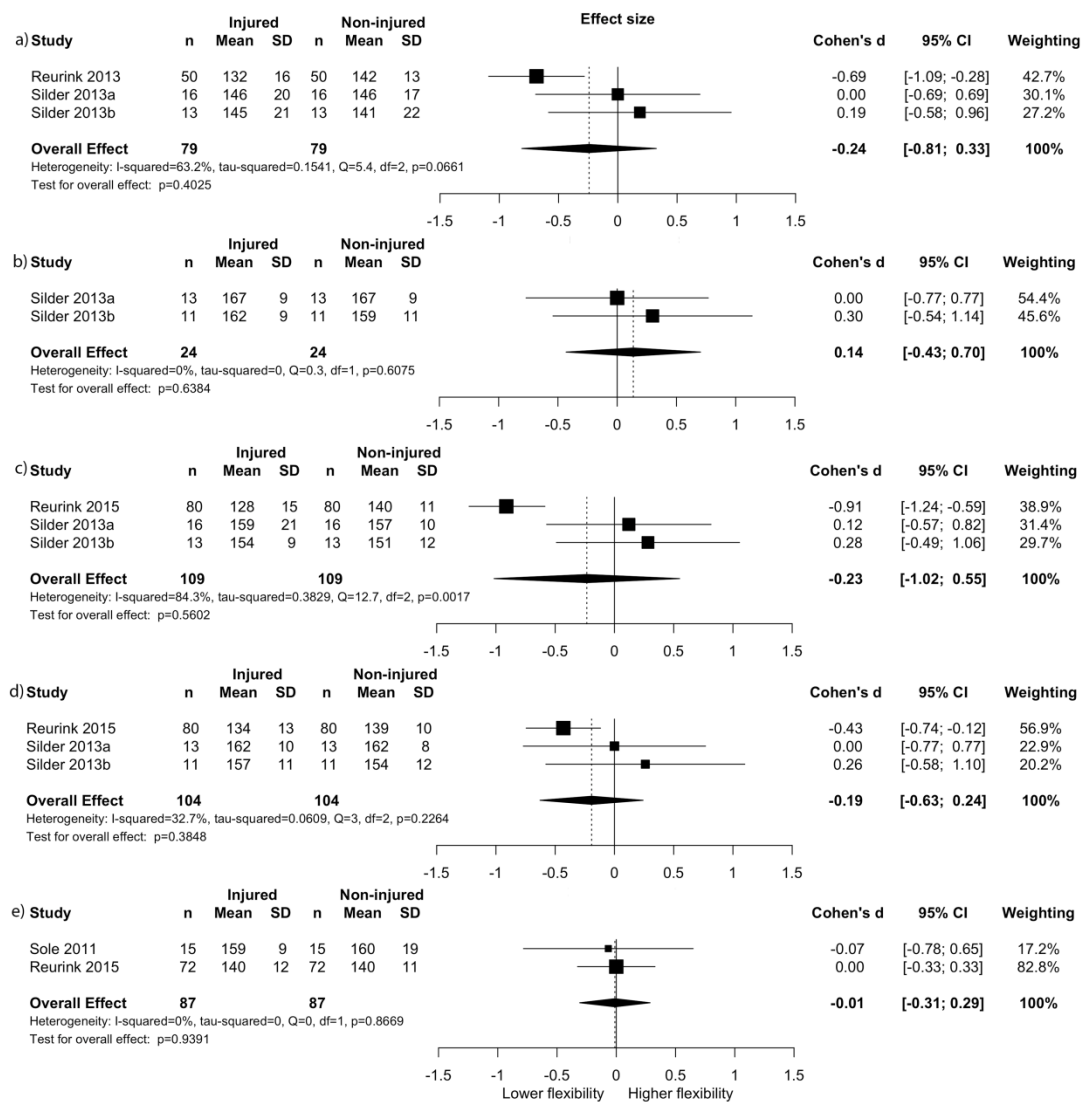


Figure 11. Forest plot for the knee extension assessments of range of motion at a) passive, <10 days post injury, b) passive, 20-30 days post injury, c) active, <10 days post injury, d) active, 10-30 days post injury, and e) active, >100 days post injury. Note that one study (26) had two subgroups, a, PATS; b, PRES.