No sign of weakness: a systematic review and meta-analysis of hip and calf muscle strength after anterior cruciate ligament injury

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ABSTRACT
Objective We aimed to determine hip and lower-leg muscle strength in people after ACL injury compared with an uninjured control group (between people) and the uninjured contralateral limb (between limbs).

Design Systematic review with meta-analysis.

Data sources MEDLINE, EMBASE, CINAHL, Scopus, Cochrane CENTRAL and SportDiscus to 28 February 2023.

Eligibility criteria Primary ACL injury with mean age 18–40 years at time of injury. Studies had to measure hip and/or lower-leg muscle strength quantitatively (eg, dynamometer) and report muscle strength for the ACL-injured limb compared with: (i) an uninjured control group and/or (ii) the uninjured contralateral limb. Risk of bias was assessed according to Cochrane Collaboration domains.

Results Twenty-eight studies were included (n=23 measured strength ≤12 months post-ACL reconstruction). Most examined hip abduction (16 studies), hip extension (12 studies) and hip internal rotation (7 studies) strength. We found no meaningful difference in muscle strength between people or between limbs for hip abduction, extension, internal rotation, flexion or ankle plantarflexion, dorsiflexion (estimates ranged from −9% to +9% of comparator). The only non-zero differences identified were in hip abduction (24% stronger on ACL limb (95% CI 8% to 42%)) and hip external rotation strength (12% deficit on ACL limb (95% CI 6% to 18%)) compared with uninjured controls at follow-ups >12 months, however both results stemmed from only two studies. Certainty of evidence was very low for all outcomes and comparisons, and drawn primarily from the first year post-ACL reconstruction.

Conclusion Our results do not show widespread or substantial muscle weakness of the hip and lower-leg muscles after ACL injury, contrasting deficits of 10%–20% commonly reported for knee extensors and flexors. As it is unclear if deficits in hip and lower-leg muscle strength resolve with appropriate rehabilitation or no postinjury or postoperative weakness occurs, individualised assessment should guide training of hip and lower leg strength following ACL injury.

PROSPERO registration number CRD42020216793.

INTRODUCTION
Knee muscle (quadriceps and hamstrings) strength deficits are well-established after ACL injury and reconstruction surgery and are a key focus of rehabilitation guidelines. Quadriceps and hamstring weakness can persist for up to 20 years post-ACL injury and may increase the risk of re-injury and post-traumatic osteoarthritis (OA). The strength of other lower-limb muscles following ACL injury is less clear, despite hip and lower-leg (calf) muscles playing a critical role when executing most weight-bearing daily activities and more complex sporting and athletic tasks.

The hip and calf muscles are integral to knee movements, with potential impacts on risk of knee joint disease. Hip muscle strength is commonly impaired in many knee conditions, such as patellofemoral pain, patellar tendinopathy and non-traumatic knee OA, but consistent causal links to the development or worsening of knee conditions are not seen. Through its direct link to the knee via the kinetic chain, the hip complex contributes frontal plane knee stability/control (eg, potentially reducing dynamic knee valgus) which if impaired may lead to worsening symptomatic and structural outcomes at the knee. Adequate hip muscle strength may be vital after ACL injury, where the risk of post-traumatic OA is significantly higher. Lower hip external rotation strength at 1 year was associated with greater odds of worsening knee structural outcomes 5 years after ACL reconstruction (ACLR). Better hip muscle strength may also be linked to better functional performance—an important benchmark for return to sport and
activity. Similarly, lower-leg muscles (such as of the calf) may impact knee function due to the gastrocnemius’ anatomical origin being proximal to the knee. Indeed, the calf is emerging as a key contributor to knee joint stability and compression forces, with potential implications for future re-injury and structural outcomes following ACL injury.

Several authors have suggested hip muscle weakness might be a problem requiring treatment after ACL injury, and rehabilitation trials often include hip and calf muscle strengthening components. Yet hip and/or lower-leg muscle strength are not clearly summarised after ACL injury. To inform the planning and design of future rehabilitation programmes, the aim of this systematic review was to determine hip and lower-leg muscle strength in ACL-injured limbs compared with (i) uninjured controls and (ii) the uninjured contralateral limb.

METHODS

This systematic review adheres to Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. It was prospectively registered (PROSPERO: CRD42020216793) as part of a group of systematic reviews investigating changes in strength and functional performance after ACL injury. This review focuses on hip and lower-leg strength, others will focus on quadriceps and hamstring strength as well as functional test performance. There were three protocol deviations. The effect size in our analysis was changed from standardised mean differences to the ratio of means (RoM), to enable inclusion of studies reporting only limb symmetry indices (see ‘Data analysis’ section). This measure is also likely to be more clinically interpretable. Second, meta-analyses were conducted if two or more studies were available for analysis (instead of three), given the lack of data for some measures. Lastly, we did not present comparisons between the uninjured leg of ACL-injured groups and uninjured controls, as it was beyond the scope of this paper given the breadth of this review. All deviations were made prior to data analysis commencing.

Eligibility criteria

We included studies of primary ACL injury (managed with surgical reconstruction or rehabilitation) with a mean participant age of 18–40 years at the time of ACL injury. We did not restrict inclusion on any other injury (eg, concomitant injuries), rehabilitation (eg, type, duration) or surgical (eg, graft type) characteristics. Studies that reported a quantitative measure of hip or lower-leg muscle strength measured by an isokinetic or handheld dynamometer were included. Muscle strength had to be reported for the ACL-injured limb and (i) an uninjured control group (between-person comparison) and/or (ii) the uninjured contralateral limb (between-limb comparison). Studies that reported unilateral strength without comparison, or did not specify the injured limb (eg, reported dominant and non-dominant side) were excluded. We did not restrict based on timing of strength assessment since surgery/injury. We also did not limit based on study design, except for excluding studies of fewer than 10 participants.

Search strategy

A search strategy was piloted based on key articles identified in the literature and encompassed two elements: population (ACL injury) and outcome (strength or physical performance). We used the same search for all papers as part of this group of reviews. Free text and Medical Subject Headings terms were combined and tailored to each database (online supplemental file 2). We searched MEDLINE, EMBASE, CINAHL, Scopus, Cochrane CENTRAL and SportDiscus from inception to 28 February 2023, limiting to humans where possible but with no restrictions on language. In addition, we searched OpenGrey, as well as checking reference lists of included articles and ahead of print sections of key physical therapy, rehabilitation and sports medicine journals.

Study selection

Two authors (MG and either MH or BP) independently screened titles and abstracts against eligibility criteria, before screening full texts of relevant studies for final inclusion. Disagreements were discussed until a consensus was reached, and a third reviewer consulted for any disagreements as reported previously.

Data extraction

Data were extracted using a prepiloted customised extraction form, by one author (MG) and checked by another (MH). Information extracted included study design, country of study, demographic details for each group (eg, age, sample size, number of women, body mass index, Tegner activity level, graft type), outcome measure details, timepoint of data collection and outcome data (reported as injured limb, non-injured limb, control limb or limb symmetry index (LSI)). For studies with multiple timepoints (eg, cohort studies or randomised controlled trials), we extracted data at all available timepoints. Where data were presented only graphically, we extracted data using Plot Digitizer (V2.6.8, http://plotdigitizer.sourceforge.net/). Authors were contacted to request any data unable to be extracted from the manuscript. If no response was received after two attempts and the study had no other data available for extraction, the study was excluded. Non-English studies were translated using DeepL (http://www.deepl.com).

Risk of bias assessment

We assessed risk of bias according to domains outlined by Cochrane Collaboration guidelines (online supplemental file 3) random sequence generation, allocation concealment, blinding of therapist and patient, blinding of assessor, outcome measurement, bias in selection of participants, attrition and statistical analysis. Several different study designs were included, meaning some risk of bias domains were not assessed in many studies (eg, bias related to randomisation or group allocation in cross-sectional studies). Two reviewers (MG, MH) assessed risk of bias independently with any disagreements resolved by discussion, and a third reviewer (AGC) consulted as required. Certainty of evidence was defined using the Grading of Recommendations, Assessment, Development and Evaluations, assessed by two reviewers (MG, AGC). We assessed the certainty for each strength outcome and comparison (between-person and within-person). As most studies were observational, baseline grading was ‘low’, with criteria used for downgrading evidence detailed in online supplemental table 11.3.

Data analysis

Effect sizes for meta-analyses were calculated as ratio of means (RoM). This method expresses the effect as the mean of one group divided by the mean of the comparison. A detailed description on the calculation of variance is published elsewhere. For between-limb comparisons (ie, within person), these data are paired/correlated and so the RoM effect calculation is modified slightly to account for this, by providing a correlation between limbs. As the between-limb correlation

was not reported by any study, we estimated this based on our strength data as $r=0.85$. The RoM allows for simplified clinical interpretation (eg, a RoM of 0.8 = ACL limb is 0.8 × strength of the comparator, or 20% deficit), compared with traditional metrics such as the standardised mean difference. The RoM is widely used in ecological research, and allowed for incorporation of studies that present data only as LSI. For studies that only reported LSI, we approximated these to the RoM using formulae (online supplemental file 4). Findings that were not presented as median (SD) format (eg, SE, 95% CI) were transformed with appropriate formulae. Data presented as median and IQRs were transformed to mean and SD according to published methods.

Data were pooled based on the strength outcome (eg, hip abduction) and the type of comparison: (i) between person (compared with uninjured control group) or (ii) between limbs (compared with uninjured contralateral limb). We selected the dominant limb of the control group for comparison where possible. To ensure data from each study were only included once per outcome, per comparison in each meta-analysis, the following decisions were used: (i) where studies reported multiple different measures for the same outcome (eg, isokinetic testing at 60°/s and 120°/s), the measure that was most similar to other studies was selected for pooling; (ii) where a study reported outcomes across multiple timepoints, the time-point closest to 12 months post-injury or reconstruction was selected. Data from < 1 month postinjury/reconstruction, or from ACL deficient groups were not included in meta-analysis, and were summarised narratively. Random effect meta-analysis with a restricted maximum likelihood estimator was used when more than two studies were available for pooling for each outcome and comparison. Where possible (more than two studies), we stratified our analyses based on time since ACLR as: (i) short-term (≤12 months) or (ii) long-term (>12 months). Analysis was conducted using the ‘metafor’ and ‘meta’ packages in RStudio. We calculated $\tau^2$ to assess between-study variance, $I^2$ to assess total variability explained by between-study heterogeneity, and presented 95% prediction intervals for all analyses (estimate of interval where future observations could fall). We performed a leave-one-out/influence analysis to check the robustness of results for each meta-analysis of more than two studies (online supplemental file 9), by examining the impact of removing a study on overall estimates and heterogeneity statistics (‘influence’ command from metafor and ‘metafin’ from meta package). Any data that could not be summarised quantitatively were synthesised narratively. Scripts and all data used are publicly available: https://github.com/mgirdwood7/hipcalf_acl_sr

Data from each study per outcome (online supplemental tables 7–9). All except one study40 included participants managed with surgery (all ACLR except one study of ACL repair). Most studies measured strength in the first 12 months postsurgery, with only three studies measuring at >36 months postsurgery (table 1). Only six studies reported Tegner activity levels, with mean/median scores ranging from 5 to 7. Five studies recruited specifically athletes,47–49 with two at elite levels,41 50 while four others specified recreationally active populations.20 42 43 51

Isometric testing with a hand-held dynamometer was the most common method of strength assessment (16 studies). The remaining 12 studies measured slow speed concentric strength using computerised isokinetic dynamometers (≤120°/s), with 2 also measuring eccentric strength.36 38 Hip external and internal rotation strength were only measured with hand-held dynamometers. All studies measuring plantarflexion and dorsiflexion strength except one used an isokinetic dynamometer. Method of strength assessment for each study is listed on each forest plot and detailed in online supplemental table 5.1.

### Risk of bias

All except three studies suffered from high risk of bias of assessor blinding (ie, the assessor was aware of the injury status of the test limb, online supplemental file 7). Outcome measurement was reliably reported with detailed methodology and low risk of bias for all except four studies. Ten studies suffered from unclear selection bias. Of the intervention trials included, three out of six had high risk of bias in randomisation methods (sequence generation and concealment), and blinding methods, respectively. A funnel plot was only assessed for studies measuring hip abduction strength comparing between limbs (n=12 studies, online supplemental file 6.1). On inspection, there appears some slight asymmetry (lack of small sample studies showing hip abduction weakness on the affected limb), although the Egger’s test was not statistically significant (intercept estimate 0.24, 95% CI –3.37 to 2.89, p=0.87).

The certainty of evidence was rated as very low for all muscle strength outcomes for between-person (online supplemental table 11.1) and within-person comparisons (online supplemental table 11.2). Evidence was primarily downgraded due to risk of bias and inconsistency, and also imprecision for some between-person comparisons.

### META-ANALYSES

We were able to complete meta-analyses for all main hip and lower-leg muscle groups (summary plots—figure 1). Detailed plots and statistics for all meta-analyses and sensitivity analyses are shown in online supplemental files 8 and 9, along with raw data from each study per outcome (online supplemental tables 12.1-12.8).

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**Equity, diversity and inclusion statement**

Our authorship team is gender balanced (four women and three men) with early, mid and late career researchers, although all from one country. We have made every attempt to be inclusive of data in this review, including translating four studies from other languages (Japanese and German), and requesting data from authors where possible. We have included data from 12 different countries from Europe, North and South America, Asia, Oceania and the Middle East, although no studies from Africa. Participants included in this review were a mixture of men and women, although some studies reported exclusively on men. We had hoped to investigate the effects of sex and gender on findings, however we were not powered for this.
<table>
<thead>
<tr>
<th>Study</th>
<th>Design</th>
<th>Country</th>
<th>Graft/Surgical intervention</th>
<th>Time post-ACLR (months)</th>
<th>ACL group sample size (n women)</th>
<th>Control group sample size (n women)</th>
<th>Age, mean (SD)</th>
<th>BMI, mean (SD)</th>
<th>Tegner activity level</th>
<th>Measurement device, unit of measurement</th>
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<tr>
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<td>RCT</td>
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<td>Not reported</td>
<td>HHD, kg</td>
<td>Hip abduction, hip adduction, hip flexion</td>
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<td>Case-control—healthy</td>
<td>Japan</td>
<td>Not reported</td>
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<td>9 (9)</td>
<td>22 (22)</td>
<td>29.7 (13.9)</td>
<td>Not reported</td>
<td>Not reported</td>
<td>HHD, kgf/kg</td>
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<td>Secondary analysis of RCT cohort</td>
<td>USA</td>
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<td>19.4 (5.1)</td>
<td>24.7 (3.8)</td>
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<td>Hip abduction, hip flexion, hip extension, hip internal rotation</td>
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<td>17 (11)</td>
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<td>Hip abduction, hip external rotation, hip flexion, hip internal rotation</td>
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<td>20 (8)</td>
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<td>Hip abduction, hip adduction, hip flexion, hip internal rotation</td>
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<td>BPTB, HS</td>
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<td>Hadi, et al 2019</td>
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<td>Iran</td>
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<td>3 and 6</td>
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<td>Hip extension</td>
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<td>33 (14)</td>
<td>–</td>
<td>28.5</td>
<td>25.3</td>
<td>Not reported</td>
<td>HHD, kg/kg</td>
<td>Hip abduction</td>
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<td>Harput, et al 2018</td>
<td>Cross-sectional</td>
<td>Turkey</td>
<td>HS</td>
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<td>72 (9)</td>
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<td>28 (7.6)</td>
<td>24.2 (4.2)</td>
<td>7.3 (1.4)</td>
<td>Isokinetic, N/m/kg</td>
<td>Hip abduction</td>
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<td>Plantarflexion (knee extended), dorsiflexion</td>
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<td>Cross-sectional</td>
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<td>Mixed</td>
<td>4.5, 9 and 18</td>
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<td>Ankle plantarflexion (knee extended), dorsiflexion</td>
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<td>45 (22)</td>
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<td>Median 5.5 (range 3-9)</td>
<td>HHD, N/kg</td>
<td>Hip abduction, hip adduction, hip flexion, hip internal rotation</td>
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<table>
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<tr>
<th>Study</th>
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<th>Mean (SD) Tegner activity level</th>
<th>Measurement device, unit of measurement</th>
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<td>Isokinetic, Nm/kg</td>
<td>Hip abduction, hip adduction</td>
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<td>Case-control—healthy</td>
<td>Greece</td>
<td>Mixed</td>
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<td>68 (0)</td>
<td>64 (0)</td>
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<td>Hip flexion</td>
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<td>Prospective cohort</td>
<td>Norway</td>
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<td>778 (778)</td>
<td>23.3 (4.1)</td>
<td>23.4 (0.5)</td>
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<td>HHD, kg/kg</td>
<td>Hip abduction</td>
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<td>Nicholas, et al 2001</td>
<td>RCT</td>
<td>USA</td>
<td>PT</td>
<td>Pre-op and 0.7</td>
<td>48 (19)</td>
<td>–</td>
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<td>Not reported</td>
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<td>Ankle plantarflexion (knee extended), ankle dorsiflexion</td>
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<td>Noehren, et al 2014</td>
<td>Case-control—healthy</td>
<td>USA</td>
<td>Mixed</td>
<td>7.3</td>
<td>20 (20)</td>
<td>20 (20)</td>
<td>21.1 (5.9)</td>
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<td>6.5 (1.6)</td>
<td>HHD, Nm/kg</td>
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<td>Rahova, et al 2022</td>
<td>Case-control—healthy</td>
<td>Turkey</td>
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<td>20 (6)</td>
<td>20 (0)</td>
<td>24.5 (5.3)</td>
<td>23.5 (1.2)</td>
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<td>HHD</td>
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<td>Phatome, et al 2019</td>
<td>Case series</td>
<td>Indonesia</td>
<td>Peroneus longus</td>
<td>6</td>
<td>31 (9)</td>
<td>–</td>
<td>27.6 (8.7)</td>
<td>Not reported</td>
<td>Not reported</td>
<td>HHD</td>
<td>Ankle eversion, halluc plantarflexion</td>
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<td>Rhim, et al 2020</td>
<td>Case-control—healthy</td>
<td>South Korea</td>
<td>HS</td>
<td>Pre-op and 12</td>
<td>32 (20)</td>
<td>32 (17)</td>
<td>30 (7)</td>
<td>22 (2)</td>
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<td>Ankle plantarflexion (knee extended), ankle plantarflexion (knee flexed)</td>
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<td>Sullivan 2022</td>
<td>Case-control</td>
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<td>10.4</td>
<td>18 (8)</td>
<td>–</td>
<td>20.8 (6.3)</td>
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<td>Not reported</td>
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<td>Hip abduction</td>
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<td>Tate, et al 2017</td>
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<td>USA</td>
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<td>12 (7)</td>
<td>20.8 (2.1)</td>
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<td>Not reported</td>
<td>HHD, N/height×BM</td>
<td>Hip abduction, hip extension</td>
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<td>Thomas, et al 2013</td>
<td>Case-control—healthy</td>
<td>USA</td>
<td>BPTB</td>
<td>Pre-op and 7.0</td>
<td>15 (7)</td>
<td>15 (8)</td>
<td>20.3 (5.4)</td>
<td>Not reported</td>
<td>Not reported</td>
<td>Isokinetic, Nm/kg</td>
<td>Ankle plantarflexion (knee extended), ankle dorsiflexion, hip abduction, hip adduction, hip extension, hip flexion, hip internal rotation</td>
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<td>Tyler 2004</td>
<td>RCT</td>
<td>USA</td>
<td>BPTB</td>
<td>2.8</td>
<td>60 (27)</td>
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<td>Not reported</td>
<td>HHD, LSI</td>
<td>Hip abduction, hip adduction, hip flexion</td>
</tr>
<tr>
<td>Urabe, et al 2002</td>
<td>Case series</td>
<td>Japan</td>
<td>HS-ST</td>
<td>Pre-op, 3, 6, 9, 12</td>
<td>44 (20)</td>
<td>–</td>
<td>32.7 (range 16–47)</td>
<td>Not reported</td>
<td>Not reported</td>
<td>Isokinetic, Nm/kg</td>
<td>Hip adduction</td>
</tr>
</tbody>
</table>

ACLR, ACL reconstruction; BM, body mass; BMI, body mass index; BPTB, bone-patellar tendon-bone; HHD, hand-held dynamometer; HS, hamstring; kgf, kg force; LSI, limb symmetry index; mixed, multiple different graft types; Nm, Newton metres; Pre-op, pre-operatively; RCT, randomised controlled trial.

Systematic review

Hip abduction

We found no evidence for a difference in hip abduction strength between ACL-injured limbs and uninjured controls (ACL n=266, control n=926, 9 studies), or between limbs for ACL-injured individuals (n=473, study 12 studies), for both short-term and long-term follow-ups (figure 2). Results were robust to omission of any study (online supplemental figure 9.1). One study also measured hip abduction strength eccentrically (estimate not included in meta-analysis), finding no difference between limbs.46

Hip adduction

We found 24% (95% CI 8% to 42%) stronger hip adductors on the ACL-injured limb compared with uninjured controls (ACL n=62, control n=62, 3 studies, online supplemental figure 8.1), although this result was fragile to omission of two studies (online supplemental figure 9.2).47 57 There was no difference between limbs in ACL groups (n=166, 5 studies, online supplemental figure 8.1). Omission of three studies lowered I2 values, but did not significantly alter overall estimates (online supplemental file 9.2).50 51 57

Hip external rotation

Hip external rotation strength was lower (−12% (95% CI −6% to −18%)) in ACL-injured people compared with uninjured controls at long-term follow-ups (ACL n=72, control n=100, 2 studies), but not in the short-term (−1% (95% CI −22% to +25%), ACL n=49, control n=77, 3 studies, figure 3). When pooling across all timepoints, we found no difference between ACL groups and uninjured control groups for hip external rotation strength (ACL n=121, control n=177, 5 studies, figure 3). This result was fragile to omission of two studies,46 61 suggesting caution in this finding (online supplemental 9.3). When comparing between limbs in ACL-injured groups, we found no difference in hip external rotation strength (n=186, 3 studies), with significant heterogeneity of effects, and overall estimate fragile to omission of one study.62

Hip internal rotation

There was no difference in hip internal rotation strength in ACL-injured people compared with uninjured controls (ACL n=64, control n=95, 2 studies, online supplemental figure 8.2). There was no evidence for a difference in strength between limbs in ACL-injured populations (n=166, 2 studies, online supplemental figure 8.2). Both comparisons were limited by significant variability of findings.

Hip extension

Hip extension strength was not different between ACL-injured people and uninjured controls (ACL n=139, control n=182, 6 studies, figure 4), or between limbs in ACL-injured groups (n=304, 9 studies). Both comparisons showed considerable

Figure 1 Summary forest plot of overall meta-analysis estimates for each outcome, for comparison with uninjured control group (left) and with uninjured limb (right). Black diamonds are summary estimates (95% CI) from meta-analyses with orange bands representing the prediction intervals. Grey shaded region indicates ±10% difference in strength. ACLR, ACL reconstruction.

Figure 2 Forest plots from hip abduction meta-analyses for comparison with uninjured control group (left) and with uninjured limb (right). ACL reconstruction; Con, concentric; HHD, hand-held dynamometer; ISK, isokinetic dynamometer; RoM, ratio of means.
variability in effects, especially when comparing with uninjured controls ($I^2=72\%$, prediction interval=0.61 to 1.67). Results were consistent for short-term and long-term follow-ups, and overall effect estimates were consistent with omission of any study, although omission of three studies lowered $I^2$ values (online supplemental figure 9.3).20 44 53

### Hip flexion
There was no difference in hip flexion strength in ACL groups compared with uninjured controls (ACL n=103, control n=99, 3 studies, online supplemental figure 8.3). Comparison between limbs in ACL-injured people showed no difference in flexion strength (n=265, 6 studies, online supplemental figure 8.3). This finding was affected by significant variability of effects ($I^2=97\%$, prediction interval=0.12 to 7.94). Omission of one study54 lowered $I^2$, but did not alter the overall estimate (online supplemental figure 9.5).

### Plantarflexion strength
Plantarflexion strength was measured by six studies. No difference was found between ACL and uninjured control groups (ACL n=67, control n=67, 3 studies, online supplemental figure 8.4), or between limbs in ACL-injured groups (n=175, 6 studies, online supplemental figure 8.4). Only one study measured plantarflexion strength in a knee flexed position (in addition to knee extended position included in meta-analysis), finding no difference comparing with uninjured controls, but significantly greater strength (10%) on the ACL limb compared with the contralateral limb.

### Dorsiflexion strength
Four studies measured dorsiflexion strength, with no differences shown when compared with an uninjured control group (ACL n=35, control n=35, 2 studies, (online supplemental figure 8.5) or to the contralateral limb (n=143, 5 studies).

### Other outcomes
Two studies measured strength in the first month after ACLR and were not included in any meta-analyses. One study measured hip flexor, hip extensor, hip abductor and hip adductor strength on the fourth day after surgery, finding deficits ranging from 50% to 80% on the ACLR limb compared with the contralateral limb.59 Another study investigating the impact of tourniquet use 3 weeks postsurgery, showed ~15%–20% lower dorsiflexion strength, and ~10% lower plantarflexion strength (knee flexed at 30°).54 Findings were not affected by tourniquet use. One study measured ankle eversion and first ray plantarflexion strength (after use of peroneus longus autograft), and found no differences between limbs.55 Five studies measured strength preoperatively, findings summarised in online supplemental 10.

### ACL deficient populations
One study measured non-surgically managed ACL injuries 12 months postinjury (n=12) and found no differences between limbs for hip extension, hip flexion, plantarflexion or dorsiflexion strength.40

### DISCUSSION
Results from our meta-analyses do not support the notion that widespread hip or lower-leg muscle weakness exists after ACL reconstruction.

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**Figure 3** Forest plots from hip external rotation meta-analyses for comparison with uninjured control group (left) and with uninjured limb (right). HHD, hand-held dynamometer; ISK, isokinetic dynamometer; Con, concentric; ACL reconstruction; RoM, ratio of means.

**Figure 4** Forest plots from hip flexion meta-analyses for comparison with uninjured control group (left) and with uninjured limb (right). ACL, anterior cruciate ligament; ACLR, ACL reconstruction; CI, CI interval; HHD, hand-held dynamometer; ISK, isokinetic dynamometer; RoM, ratio of means.
injury. We found no consistent evidence for a difference between people (ie, compared with uninjured controls), or within people (ie, comparison with the uninjured contralateral limb), with the largest number of studies available for hip abduction and extension strength. The only non-zero differences identified were 12% (95% CI 6% to 18%) weaker hip external rotators and 24% (95% CI 8% to 42%) stronger hip adductors in the ACL-injured limb compared with uninjured controls, however both results were pooled from only two studies. Certainty of evidence was very low for all outcomes. Many between-person estimates were affected by low numbers of included studies, as well as heterogeneity of effects with wide prediction intervals, suggesting caution in interpreting these findings. Individualised assessment should guide prescription of hip and lower-leg muscle strengthening.

Our review provides the first comprehensive summary of hip and lower-leg muscle strength after ACL injury. Contrary to our expectations, there was no consistent evidence for widespread lower-limb muscle weakness (ie, across different movement directions), nor weakness with large effect sizes. SE of measurement for hip and lower-leg strength assessment is generally between 5% and 10%. Acknowledging the limitations of sample sizes and variability of study effects, almost all of our point estimates and summary findings (except for hip adduction strength) showed muscle strength outcomes within 5%–10% of the comparator (most data from 6 to 12 months post-ACLR), suggesting even with these limitations, major weakness such as is commonly reported for the quadriceps and hamstrings is unlikely to be present in the hip and lower-leg muscles after ACL injury.

Quadriceps and hamstring weakness is near universal after ACL injury and a major clinical impairment that continues to be a challenge, despite extensive rehabilitation efforts. Based on our findings, persistent weakness may be contained to the thigh muscles. Pain, effusion and immobilisation caused by ACL injury and reconstruction undoubtedly affect the knee most, however it is surprising that other lower-limb muscles such as the hip and calf appear unaffected, given their critical contributions to knee movement and control. Unlike the thigh, the hip and lower-leg muscles could be less affected by central nervous system changes postinjury/surgery, that contribute to persistent thigh muscle weakness. The hip and calf are also unlikely to be affected by significant arthropathic muscle inhibition or changes to activation commonly seen in the quadriceps and hamstrings as a result of pain and effusion at the knee joint. Certainty of evidence was very low for all outcomes, and most studies reported strength between 6 and 12 months post-ACLR). As further evidence emerges, it is possible our results could change. Hip abduction strength had the most evidence, with narrow prediction intervals, where new papers are unlikely to alter our estimates, although certainty of evidence was still very low.

Current rehabilitation approaches for the hip and lower-leg muscles may adequately restore comparable muscle strength to the levels of uninjured controls. Training non-thigh muscles is frequently recommended for knee injury rehabilitation (including ACL injury). No ACL clinical guidelines specifically recommend hip or calf muscle strengthening, nor do major intervention studies measure the impact of training these muscles. Unfortunately, rehabilitation was often insufficiently described in the included studies, leaving us to speculate. Rehabilitation completion and adherence was likely variable for participants in these studies, as previous studies have reported <50% of people engaged with a therapist for rehabilitation beyond 3 months post-ACLR. On the other hand, some participants may have had structured training as part of study protocols in randomised controlled trials. Although it is possible that non-thigh muscles were not overly impaired pre-injury or postsurgery, this seems less likely, as hip muscle weakness is evident in some people pre-injury, and two studies included in this review showed large deficits in hip and lower-leg strength in the first 2-3 weeks post-reconstruction. Further longitudinal studies measuring muscle strength across multiple timepoints may help to understand the trajectory and cause of any hip muscle strength changes.

Thigh muscle weakness after injury may increase the demand on hip and lower-leg muscles, and these non-knee muscles may need to be stronger than in uninjured people. Indeed, our results showed stronger adductors in the ACL-injured limb compared with uninjured controls. Other studies have found greater hip extension strength in those with weaker quadriceps after ACLR, and change to a more ‘hip-dominant’ strategy shown across movements such as hopping. Before we can recommend training a more hip dominant strategy to compensate for quadriceps weakness, we need to determine whether a clinically meaningful link exists between greater hip strength and better structural and self-reported outcomes, and whether this can be targeted with tailored strength training.

For clinicians, restoring hip muscle strength may still be a priority—individualised assessment of the impairments and goals of each person should be considered. However, our results might indicate that routine isolated hip muscle strength training may not be necessary in all people after ACL injury, acknowledging that wide prediction intervals for some results (eg, hip extension) could suggest significant variability from our estimates in some people. Many of our results are from data between 6 and 12 months post-ACLR, although deficits might still be present earlier post-operatively. Maintenance of strength, particularly in the early postoperative phase, may be another justification for adding hip and calf training to rehabilitation. Incorporating multijoint movements, functional tasks and closed kinetic chain exercises will also target the broader kinetic chain, including the hip and lower-leg muscles. Targeting the hip and calf muscles may also benefit athletic performance. Guidelines and consensus exercises recommend a key focus on regaining quadriceps strength after injury, and this should remain a top priority. For participants with hip and lower-leg muscle impairments identified during rehabilitation, targeted strength training may be appropriate. Monitoring hip muscle strength is feasible and reliable in the clinic with a hand-held dynamometer, and can be used to guide training goals. Hip and lower-leg muscle strength within 5%–10% of either normative data, or the contralateral leg may be an indicative standard for people to aim for after ACL injury.

This review has several limitations. Many comparisons were affected by small number of studies and included participants. Where possible (more than two studies), we conducted a leave-one-out sensitivity analysis to assess the robustness of findings, and overall effect estimates for most outcomes were unaffected by removal of a study. Almost all included studies failed to blind the outcome assessor (ie, strength tester), which is relevant given assessor encouragement can impact the voluntary effort needed to achieve an accurate measure of peak strength. It may also be important for hand-held dynamometry where the assessor must match or break the force. Many case-control studies were also affected by unclear selection bias, a common problem for this research design, likely adding to uncertainty of prediction intervals. Comparison with an uninjured control group is important for outcomes such as muscle strength, as comparing with the uninjured contralateral leg may be affected by confounding factors including weakness pre-injury, reduced

activity post-injury and central nervous system changes.77–78 We identified two additional studies unable to be included,79 80 with hip strength outcomes reported without specifying the injured limb, or reported only as a strength ratio (eg, abduction/adduction ratio). We are also aware of five studies measuring hip muscle strength in adolescent/paediatric populations which did not fit our criteria.81–85

Another limitation was the pooling of different contraction types and strength testing methods (eg, concentric and isometric tests), which may have diluted any potential deficits. Isometric contractions may be more sensitive to showing asymmetries, as muscles can exert higher force during isometric contractions, compared with concentrically.86 87 Similarly, the hip muscles are often tested in different positions (eg, in hip neutral vs 90° hip flexion for hip rotation strength), influencing length-tension relationships which could explain some of the variability seen in our estimates.

Results from our review are most generalisable to young (age <30 years) people after ACLR from western countries. Results may be different in ACL deficient populations as well as in older or less athletic groups. We have made every attempt to be inclusive of data, including translating four studies from other languages and requesting data from authors where possible. Measuring differences between genders for strength was beyond the scope of this review, and three studies included cohorts of predominantly men. Differing timepoints and graft types may also have added to heterogeneity of effect estimates. Only four studies measured strength beyond 36 months after surgery, with the majority of our data from the short-term postsurgery (<12 months post). Lastly, most strength tests used were short duration and isometric, which may not capture all possible deficits (eg, eccentric contraction, muscle endurance).

CONCLUSION

Major and widespread hip and lower-leg muscle weakness was not a feature after ACL injury. This finding held true, irrespective of comparison group (uninjured controls or uninjured contralateral limb), but was informed by very low certainty evidence mainly from 6 to 12 months post-ACLR. The most robust evidence was for hip abduction strength, where new research is unlikely to change our estimates, showing no difference in the ACLR limb compared with a control group, or when compared with the contralateral limb. Hip internal rotation, ankle plantarflexion and dorsiflexion strength suffered from a lack of data in case-control comparisons, with limited clinically useful findings. For clinicians, training and rehabilitation decisions should be based on individualised assessment of hip and lower-leg strength, as currently it is unclear whether no postinjury weakness arises, or deficits resolve with appropriate rehabilitation.

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