

LETTER TO THE EDITOR-IN-CHIEF

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IS IT TIME TO PUT SPECIAL TESTS FOR ROTATOR CUFF-RELATED SHOULDER PAIN OUT TO PASTURE?

In their recent Viewpoint on the “passing of their sell-by date” regarding special tests for rotator cuff-related shoulder pain (RCRSP), Drs Salamh and Lewis² offer answers to 3 questions:

1. Are clinicians capable of identifying the structure(s) causing the symptoms?
2. Do imaging findings explain the cause of symptoms?
3. When surgeons perform various shoulder procedures, can they be certain they are operating on the tissue causing the symptoms?

While all 3 questions are thought provoking, only the first question can truly be reviewed from a “scope of practice” perspective. In reviewing the authors’ answer to question 1, the reader is challenged to self-reflect as to whether it is the special test that cannot identify the structure or the clinician. Similar to magnetic resonance imaging, which was not designed to “diagnose” the problem, but rather to identify the presence or absence of a suspected problem, it is the clinician’s duty to assess whether it is his or her choice of test(s) or personal experience in conducting the test(s) that prevents the identification of the problem.

While there may be over 70 special shoulder tests in clinical use, this should not suggest that all 70 of the identified tests are sensitive or specific to the presence of shoulder pathology. Nor should it suggest that the tests are being utilized

appropriately or in combination with each other when examining a patient with RCRSP. Furthermore, the use and validity of any special test depend on the clinician’s knowledge of the structures being tested and appropriate choice of selected complementary tests that assist in narrowing the clinician’s suspicions or hypothesis. If this Viewpoint² is accepted as fact, the argument of “passing their sell-by date” could easily be made for every special test currently available to physical therapists, leading to conversations on special tests of the hip, spine, knee, etc.

One suggestion, prior to accepting that special tests have passed their sell-by date, is to consider reviewing the educational process and implementing more rigorous and applicable overlap in pathology, neurology, and tactile skills utilized in orthopaedic assessment. In particular, one could apply the same standards, expectations, and rigor employed when examining and treating a patient with stroke or spinal cord impairment to the orthopaedic patient. This would strengthen the educational process, by holding students and practicing clinicians accountable for being aware of ongoing developments in the literature and ensuring the clinician’s knowledge of anatomy, neurology (increased awareness and application of mechanoreceptors present), physiology, and refined clinical skills.

In conclusion, perhaps it is not the special test that has reached its sell-by date, but rather the educational model that is too narrow or the clinician who is functioning under “time constraints” to complete a thorough physical examination. While the authors² include a table outlining components of the examination elements for RCRSP, it is this reader’s opinion that “special tests” are necessary and invaluable in completing the “assess impairments” section of the table presented. While not universal to all special tests, the testing process and the test employed are enhanced through the use of “clusters.”¹ Acknowledging the challenge described, there are many of us within the

physical therapy profession who would benefit from and enhance our examination skills through a review of the current literature, leading to an expansion of our horizons and sharpening of the thoroughness of our examination skills. Accepting that challenge will lead us to use the knowledge we have built on that foundation and provide an opportunity to serve the patients who entrust their care to us in a progressive and modern way. Perhaps, in the end, it is not the tests that have sell-by dates, but the clinician who stops moving forward.

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2. Salamh P, Lewis J. It is time to put special tests for rotator cuff-related shoulder pain out to pasture. *J Orthop Sports Phys Ther*. 2020;50:222-225. <https://doi.org/10.2519/jospt.2020.0606>

RESPONSE

We thank Dr Lombardi for his letter. Dr Lombardi states that only 1 of the 3 questions we posed⁵ can be viewed from a “scope of practice” standpoint. We respectfully disagree.

Question 2: Do Imaging Findings Explain the Cause of Symptoms?

There is an incorrect assumption that only physical therapists read and contribute to *JOSPT* and that they don’t refer people for scans. Physical therapists

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in the United Kingdom refer for shoulder ultrasound, magnetic resonance imaging, X-ray, etc. This is also true in the US military. Whether referring or not, physical therapists help people understand and interpret the scan findings. Typically, in most cases of RCRSP, imaging findings shouldn't be considered to reveal the definitive source of symptoms, as they are probably normal changes associated with aging, such as wrinkles or graying hair, that are never felt and only "hurt" when they are seen on a scan.

Scans are the so-called gold reference standards that clinical tests are compared against to determine specificity and sensitivity, positive and negative predictive values, and likelihood ratios. It is unquestionably within scope to be aware of the utility of the reference tests to detect symptomatic pathology.

Question 3: When Surgeons Perform Various Shoulder Procedures, Can They Be Certain They Are Operating on the Tissue Causing the Symptoms?

Shared decision making, the process whereby clinicians and patients work together, placing the individual at the center of decisions about his or her care, requires that all assessment and management options be explored, along with their value, harms, and benefits. We wonder whether future generations will look back on us and ask, "Why, when many elective surgical procedures were already shown to perform no better than placebo and when there was no certainty that the tissue causing the symptoms in RCRSP could be identified with imaging and clinical tests, did they not find it incumbent upon themselves to inform people considering surgery and instead deem this shared knowledge outside their scope of practice?"

With respect to question 1 ("Are clinicians capable of identifying the structure(s) causing the symptoms?"), Dr Lombardi states, "... it is the clinician's

duty to assess whether it is his or her choice of test(s) or personal experience in conducting the test(s) that prevents the identification of the problem." We agree. Following our assessment, we concluded that the special tests for RCRSP add no value to diagnosing the problem.⁵ There are myriad reasons why.²⁻⁴

We focus on 2 issues to support our contention. First, Dr Lombardi states, "... the use and validity of any special test is dependent on the clinician's knowledge of the structures being tested and appropriate choice of selected complementary tests that assist in narrowing further the clinician's suspicions or hypothesis." It is possible that *validity* is being confused with *sensitivity* and *specificity*. A valid special test is able to accurately test what it sets out to test. If a special test is referenced to a test that cannot empirically determine whether the observed structural changes are the cause of symptoms, then we argue the special test has no value. Special tests were born in an era when pain was thought to be a product of nociception. In the 2020s, clinicians understand that the experience of pain is more complex and may not relate to the shoulder tissues being stretched, contracted, or compressed. In 1992, Clark and Harryman¹ described the rotator cuff as being a confluence of inseparable tendons, interwoven with capsular tissue and intimately related subacromial bursa. This anatomy, while being perfectly suited to stabilize and move the shoulder, would make it impossible to apply a test to identify a specific structure. The anatomical structure challenges Dr Lombardi's argument that special tests for RCRSP are required and are invaluable.

Second, Dr Lombardi advocates for the use of "test clusters" (ie, multiple special tests to improve the likelihood at arriving at the correct pathology-based diagnosis). We believe that adding the results of one fundamentally flawed special test to another may only exacerbate ambiguity and may not yield anything

more than uncertainty. This will only be resolved when we have unequivocal gold standard reference tests. Currently, we suggest that the reference standards in use to "validate" the special tests may not even be a precious metal.

We agree with Dr Lombardi's statement that it is time for the value of every special test in current use for the hip, spine, and knee to be considered. We suspect, once analyzed, that many of these tests will also need to be gracefully retired.

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We are pleased to showcase additions to the JOSPT stable in 2020. The big-ticket items are the JOSPT Insights podcast and the JOSPT blog (more on these below).¹ Subscribers will also find other new features on the JOSPT website.

Ready for Digital Lift-off

The redesigned JOSPT website launched in March 2020, with a responsive design that automatically adjusts to screen size, and an enhanced ability to host new digital products. It is now easier than ever to find answers to clinical questions in a variety of media, on whatever device you are using. You will find the JOSPT blog page and links to the JOSPT Insights podcast on the site. Coming soon are embedded videos accompanying clinical practice guidelines.

The popular Evidence in Practice series, led by Dr Steven Kamper, has a new home as a dedicated collection

on the JOSPT website (www.jospt.org/topic/evidence_practice). The Evidence in Practice series aims to help clinicians understand and confidently apply research to their clinical practice. Recent articles have explained important concepts like the difference between statistical significance and clinical meaningfulness,³ and what the confidence interval of an effect tells you.²

Insights to Write Home About

The JOSPT Insights podcast (with Dr Chelsea Cooman and Dr Daniel Chapman as regular co-hosts) takes you beyond the research article and into

the labyrinth of clinical practice possibilities. With an experienced and influential clinician or researcher as a dependable guide, we intrepid listeners emerge with new ideas to take to the clinic.

With each episode, expect a breakdown of the important issues that impact musculoskeletal rehabilitation practice—think training load monitoring tips, tendinopathy rehabilitation pearls, and the dangers of overdiagnosis and over-treatment, to name a few—in under 30 minutes. JOSPT Insights is the perfect companion for your gym session, evening run, commute, or lunch break.

In a world inundated with ways to engage with and consume information, we appreciate that (1) the JOSPT community has plenty of options to choose from, and (2) is vigilant about the source

[EDITOR'S NOTE]

and trustworthiness of information. Our goal is to deliver clinical pearls and research gems that you can trust, to help you help the patients and athletes you work with.

Blogs, Blogs, What They Are Good for

Don't miss the opportunity to connect directly with the JOSPT community! The JOSPT blog launched in August 2020—diving straight into the International Association for the Study of Pain's revised definition of pain (www.jospt.org/doi/10.2519/jospt.blog.20200812), telehealth (www.jospt.org/doi/10.2519/jospt.blog.20200819), and Achilles tendinopathy (www.jospt.org/doi/10.2519/jospt.blog.20200826).

Dr Rachel Jermann holds the editorial reins, and she is steering a course aimed at advocacy on issues affecting the physical therapy profession, effective information dissemination, and complementing the quality research published in the pages of the *JOSPT*. Weekly posts include features such as research bites, book reviews, and opinions about the issues that impact how clinicians deliver, and patients and athletes receive, quality musculoskeletal care. The JOSPT blog welcomes ideas, suggestions, and contributions from all in the musculoskeletal rehabilitation community. We urge you to consider the JOSPT blog as a conduit for connecting with peers.

Ask, and You Shall Receive

A big thank you to all in our vibrant community who have engaged with the

JOSPT Asks series. If you have not had the opportunity to catch our weekly live chats with an influential guest from the musculoskeletal rehabilitation sphere (now up to 23 episodes), we encourage you to take a look at the videos on our Facebook page (@JOSPTOfficial) or YouTube channel.

Audience favorites have included:

- Professor Jeremy Lewis (University of Hertfordshire) answering your questions on exercise for shoulder pain (including elaborating on his recent Viewpoint with Dr Paul Salamh about retiring shoulder special tests⁴)
- Dr Sarah Haag (Entropy Physiotherapy & Wellness) highlighting what you need to know to effectively and respectfully approach pelvic health, including dispelling uncertainty around assessing the pelvic floor
- Dr Richard Willy (University of Montana) sharing tips on managing patellofemoral pain,⁵ including suggestions for return to running and plyometrics exercises

What distinguishes the JOSPT Asks series from the deluge of new online learning options is that you, the audience, ask the questions. Sincere thanks to all our guests, who have given generously of their time and wholeheartedly embraced the opportunity to connect directly with our community.

A Marketplace of Musculoskeletal Ideas

The new normal of connecting digitally brings some benefits: where once one had to pluck up the courage to ask a question

in a packed conference auditorium, raising one's head above the parapet has never been easier. Nor has the environment been so conducive to connecting in real time. What better time to engage with the community, to share your thoughts and ask your burning questions? We warmly invite you to grasp the opportunity.

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Limited Support for Trunk and Hip Deficits as Risk Factors for Athletic Knee Injuries: A Systematic Review With Meta-analysis and Best-Evidence Synthesis

Knee injuries account for 10% to 40% of all sport-related injuries,^{37,44,46,67} and can be detrimental to the well-being, future sport participation, physical performance, economic productivity, and health expenses of athletes.^{24,61,75,85} A recent

systematic review of 53 studies totaling 1 million participants found that previous knee injuries increased the likelihood of developing knee osteoarthritis 4 to 6 times.⁶² To reduce risk and prevent future injuries, greater awareness of the etiology

of and risk factors for athletic knee injury is necessary.^{3,13,77}

Neuromuscular deficits in trunk and hip function have been associated with athletic knee injury, based on expert opinion,^{32,48,64} cross-sectional stud-

ies,^{17,52,53} case-control video analysis,^{34,38,40} and quasi-experimental studies.³¹ However, in prospective studies, which are more appropriate to explore causation, there are opposing views as to whether deficits in trunk and hip neuromuscular function may be^{41,83,84} or may not be^{10,70,72} risk factors for future knee injury.

Assessing trunk and hip neuromuscular function is difficult, because it involves several physical capacities (strength, endurance, control, proprioception, force, power, torque, and muscle activation) in the production, transfer, and control of proximal forces across the lower extremity kinetic chain.^{19,32,48} Establishing causality with valid and reliable assessment methods is key to identifying athletes who may be at higher risk of sustaining knee injuries due to deficits in trunk and hip neuromuscular function, and to developing and refining injury prevention and control countermeasures, like exercise-based injury risk reduction programs.^{5,28,73}

Other reviews have explored hip-related risk factors for patellofemoral pain in isolation^{54,66} and trunk-related risk factors for lower extremity injuries in general.¹⁶ There is a need to synthesize findings from prospective cohort studies investigating

• **OBJECTIVE:** To determine whether neuromuscular deficits in trunk and hip-related function are risk factors for athletic knee injuries.

• **DESIGN:** Etiology systematic review with meta-analysis.

• **LITERATURE SEARCH:** Six online databases (MEDLINE, Web of Science, Embase, CINAHL, Scopus, and SPORTDiscus) were searched up to April 2019.

• **STUDY SELECTION CRITERIA:** Studies assessing trunk and hip neuromuscular function as risk factors for knee injuries in healthy athletic populations were included.

• **DATA SYNTHESIS:** Outcomes were synthesized quantitatively using meta-analysis of odds ratios, and qualitatively using best-evidence synthesis.

• **RESULTS:** Twenty-one studies met the inclusion criteria. There was very low-certainty evidence

that greater hip external rotation strength protected against knee injuries (odds ratio = 0.78; 95% confidence interval: 0.70, 0.87; $P < .05$). There was limited evidence that deficits in trunk proprioception and neuromuscular control, and the combination of excessive knee valgus and ipsilateral trunk angle when landing unilaterally from a jump, may be risk factors for knee injuries.

• **CONCLUSION:** Most variables of trunk and hip function were not risk factors for injuries. Further research is required to confirm whether hip external rotation strength, trunk proprioception and neuromuscular control, and the combination of knee valgus angle and ipsilateral trunk control are risk factors for future knee injuries. *J Orthop Sports Phys Ther* 2020;50(9):476-489. Epub 1 Aug 2020. doi:10.2519/jospt.2020.9705

• **KEY WORDS:** core stability, hip strength, injury prevention, knee injuries, trunk control

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the causal effects of trunk and hip-related risk factors on future knee injuries in athletes. Such a review would inform researchers and clinicians on (1) the utility of trunk and hip neuromuscular function screening to identify athletes at higher risk of sustaining future knee injuries, and (2) the need to modify trunk and hip-related content in existing exercise-based injury risk reduction programs to best address injury risk. The objective of this review was to determine whether neuromuscular deficits in trunk and hip-related function are risk factors for future knee injuries in athletic populations.

METHODS

THIS REVIEW WAS PREPARED AND conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines,⁴⁹ and registered in PROSPERO (CRD42019125974). Patients or public partners were not involved in the design, conduct, or interpretation of this systematic review.

Search Strategy

Six electronic databases (MEDLINE, Web of Science, Embase, CINAHL, Scopus, and SPORTDiscus) were searched from inception to April 2019. The following key words derived from the research questions were used to structure the search and were mapped to medical subject headings where possible: *athletes, trunk, hip, strength, control, biomechanics, knee, patellofemoral, and injuries* (see **APPENDIX A**, available at www.jospt.org, for the full search strategy). All records were downloaded to EndNote X8 (Clarivate Analytics, Philadelphia, PA), where duplicates were removed, then uploaded to Covidence (Veritas Health Innovation Ltd, Melbourne, Australia). A bibliographic hand search was also performed to supplement the electronic database search.

Eligibility Criteria

Studies were included if they met the following criteria: (1) prospective cohort

studies assessing 1 or more neuromuscular variables of trunk and hip function (trunk and/or hip strength, endurance, control, proprioception, force, power, torque, or muscle activation) in association with risk of knee injuries in healthy athletic populations, and (2) defined injuries as any acute or overuse knee injury, regardless of mechanism of injury.

To limit included studies to those of higher quality and design, the following article types were excluded: (1) expert opinion, conference abstract, case report or case series, cross-sectional and case-control study, and articles published in non-peer-reviewed journals; (2) no objective quantitative injury data were available; and (3) knee injuries considered to be nonspecific thigh injuries or nonarticular injuries localized to the tibia, fibula, or femur.

Study Selection

Two reviewers (L.C. and D.S.) independently screened the titles and abstracts of all retrieved records. The same reviewers then independently reapplied the selection criteria to full-text versions of the studies to determine eligibility. All disagreements were resolved between the 2 reviewers, with a third reviewer (E.P.) available to facilitate consensus if required. Authors were contacted via e-mail when knee injury-specific data were not available in the published manuscript.

Bias, Quality, and Certainty Assessment

Study-level bias and quality assessment was independently performed by 2 reviewers (L.C. and D.S.), using a modified

version of the Quality In Prognosis Studies (QUIPS) tool.^{25,26} The QUIPS tool consists of 6 bias domains, each consisting of 5 to 7 prompting items, each answered as yes or no. A domain has a high risk of bias if 75% or more prompting items are answered no. For the first prompting item of the study confounding domain, the important confounders were age,¹ sex,⁶³ and previous history of knee injury.⁷⁶ For a study to be considered to have a low overall risk of bias, at least 5 of the 6 bias domains, including the outcome measurement domain, had to be judged as low risk.^{25,26} Results of the study bias and quality assessment were considered as a component of the outcome certainty assessment, based on the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach.⁷ Disagreements between reviewers were resolved via consensus. No study was excluded based on bias, quality, and certainty assessment.

Outcome-level certainty assessment was performed using the GRADE approach, which was modified to apply to nonexperimental, observational studies, as in previous research.^{7,15,43} Two reviewers (L.C. and D.S.) performed the assessment independently, with disagreements settled by consensus. As per the GRADE approach, certainty levels for observational studies started at the “low-certainty” evidence classification level and were upgraded or downgraded according to the set criteria. The GRADE certainty levels and their accompanying definitions are summarized in **TABLE 1**.⁷

TABLE 1		GRADE CRITERIA	
Certainty Level	Definition		
High	Very confident that the true effect lies close to that of the estimate of the effect		
Moderate	Moderately confident in the effect estimate; the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different		
Low	Confidence in the effect estimate is limited; the true effect may be substantially different from the estimate of the effect		
Very low	Very little confidence in the effect estimate; the true effect is likely to be substantially different from the estimate of effect		
Abbreviation: GRADE, Grading of Recommendations Assessment, Development and Evaluation.			

Data Extraction

Measures of association (odds ratio [OR], risk ratio, rate ratio, hazard ratio, risk difference) between independent variables (trunk and hip-related neuromuscular risk factors) and dependent variables (athletic knee injuries) were extracted. If measures of association were unavailable, descriptive statistics (mean, SD, number of exposures) were extracted. To improve our ability to infer causation, data were extracted in the following descending hierarchy: multivariable analyses, univariable analyses that addressed confounders in study design, univariable analyses that did not address confounders in study design, and descriptive statistics. Study characteristics, population characteristics, details of neuromuscular variables of trunk and hip function, and injury type, definition,²² and prevalence were also extracted. Data were first extracted by 1 reviewer (L.C.), and all extracted data were cross-checked once by 1 of 2 other reviewers (D.S. or E.P.).

Data Analysis and Best-Evidence Synthesis

Measures of association and descriptive statistics were synthesized and analyzed with Review Manager Version 5.2 (The Nordic Cochrane Centre, Copenhagen, Denmark). Analyses were initially completed by 1 reviewer (L.C.), then verified by 1 of 2 other reviewers (D.S. or E.P.). Variables incorporating data from 3 or more studies were pooled in a meta-analysis, using random-effects methods. We used random-effects methods to account for variability between pooled studies, and to limit influences of causes of variance in sample distributions. Sensitivity analyses were planned for hip strength variables by repeating the analysis using isometric or eccentric or isokinetic measures, but only when data from 3 or more studies were available.

The OR was used as an effect measure because it was reported in most of the included studies. Where unavailable, the OR was calculated from descriptive statistics using Comprehensive Meta-

Analysis Version 2.0 (Biostat, Englewood, NJ). Due to insufficient data in the included studies, neither attempts nor assumptions were made to transform other measures of association to OR, or vice versa. Statistical heterogeneity of the pooled data was assessed using the I^2 statistic, where I^2 less than 50% was considered as not important, 50% to 75% as moderate, and greater than 75% as high heterogeneity,³⁵ and was considered as a component in the outcome-level certainty assessment using the GRADE approach.⁷ Subgroup analyses by sex, sport, and age were attempted where possible. For a more accurate picture of causal relationships, sensitivity analyses using only studies that adjusted for confounders were planned for meta-analyses.

To prevent poor parameter estimation, variables incorporating data from fewer than 3 studies were qualitatively presented in a best-evidence synthesis and not pooled in a meta-analysis. A

best-evidence synthesis was undertaken to clarify the association between independent variables and injury risk, and to assess the strength of evidence.^{69,74} Strength of evidence was classified according to the criteria listed below.⁷⁴

1. Strong evidence: at least 2 studies with high-quality and generally consistent findings in all studies (at least 75% of the studies reported consistent findings)
2. Moderate evidence: 1 high-quality study and at least 2 low-quality studies and generally consistent results (at least 75% of the studies reported consistent findings)
3. Limited evidence: generally consistent findings in at least 1 low-quality study (at least 75% of the studies reported consistent findings)
4. Conflicting evidence: fewer than 75% of the studies reported consistent findings
5. No evidence: no studies available for assessment

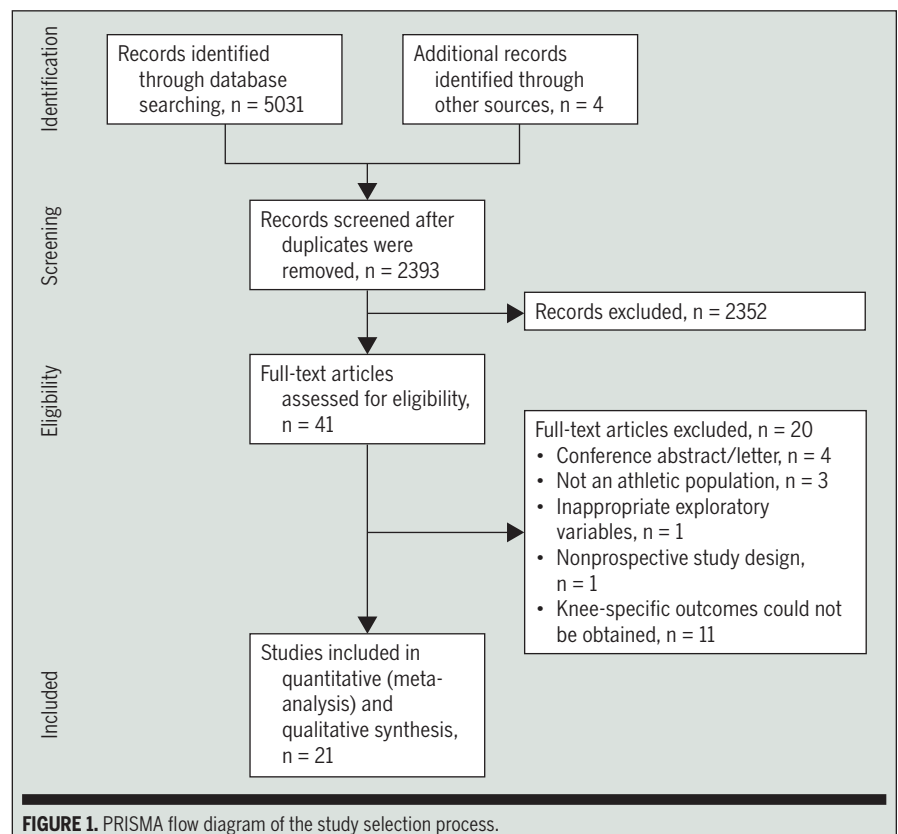


FIGURE 1. PRISMA flow diagram of the study selection process.

RESULTS

THE ONLINE DATABASE AND BIBLIO-graphic hand search yielded 2393 nonduplicate studies. Following title and abstract screening, 41 studies underwent full-text review, where a further 9 studies were excluded. Of the remaining 32 studies, authors of 14 studies were contacted for knee injury-specific data not reported in the published manuscript, and 3 responded with the requested data.^{41,79,80} Ultimately, 21 publications were included in the quantitative and qualitative synthesis (FIGURE 1).^{6,10,18,21,27,33,39,41,42,45,58,59,65,68,70,72,79,80,82-84}

Bias, Quality, and Certainty Assessment

Eight of 21 studies were at high risk of bias (TABLE 2) following study-level bias and quality assessment. The agreement

between reviewers was 88% (111 of 126 items), with all disagreements resolved by consensus. Outcome-level certainty for all meta-analyses was very low (TABLE 3).

Description of Included Studies

There were 456 knee injuries in 6348 athletes. All studies defined injuries either according to time loss or medical attention, and injuries were recorded by medical staff, coaches, or self-recorded. Nine of the 21 included studies accounted for confounding variables.^{10,18,27,42,65,68,70,83,84} Further study characteristics are summarized in TABLE 4. Nineteen variables relating to trunk and hip neuromuscular function were recorded and allocated into 3 categories: hip strength, trunk strength/control, and trunk and hip biomechanics.

Hip Strength

Hip External Rotation Strength Six studies (2452 athletes) measured hip external rotation strength in association with patellofemoral pain injuries,^{10,21,72} anterior cruciate ligament injuries,³⁹ knee overuse injuries,⁵⁹ and knee injuries in general (see FIGURE 2).^{41,59} In a meta-analysis of 5 studies,^{10,21,39,41,72} there was very low-certainty evidence (TABLE 3) that greater hip external rotation strength was associated with 22% decreased odds of future knee injuries (OR = 0.78; 95% confidence interval [CI]: 0.70, 0.87; $P < .05$). Sensitivity analysis including isometric strength data reported no change in effect sizes. The single study not included in the meta-analysis (because it reported risk ratios) supported the above findings, reporting that a 1-SD increase in external rotation strength was associated with a 35% decreased risk of overuse knee injury.⁵⁹ One study addressed confounding in a multivariable analysis.¹⁰

Hip Abduction Strength Twelve studies (4811 athletes) investigated hip abduction strength as a risk factor for athletic knee injuries.^{6,10,21,27,39,41,45,59,65,68,70,72} Eight studies were pooled in a meta-analysis that found very low-certainty evidence that hip abduction strength was not a risk factor for future knee injuries (OR = 1.11; 95% CI: 0.88, 1.40; $P = .37$) (see APPENDIX B, available at www.jospt.org).^{10,21,27,39,41,68,70,72} Sensitivity analysis of isometric strength data resulted in no change in statistical significance (OR = 1.00; 95% CI: 0.81, 1.23; $P = .97$).^{10,39,41,68,70,72}

Three studies addressed confounding;^{10,27,70} 2 with multivariable analysis.^{10,70} The subgroup analysis found no evidence that hip abduction strength was a risk factor for knee injuries in female participants (4 studies; OR = 1.65; 95% CI: 0.92, 2.95; $P = .09$) (APPENDIX B).^{27,68,70,72} Four studies that did not report ORs were not included in the meta-analyses.^{6,45,59,65} Of these 4 studies, 2 studies (both univariable analyses that did not address confounding) reported that hip abduction strength was

TABLE 2

STUDY-LEVEL RISK-OF-BIAS ASSESSMENT (QUIPS TOOL)

Included Studies (n = 21)	Item ^a						Risk of Bias
	1	2	3	4	5	6	
Bakken et al ⁶	Low	High	Low	Low	High	Low	High
Boling et al ¹⁰	High	Low	Low	Low	Low	Low	Low
Dingenen et al ¹⁸	Low	Low	Low	Low	Low	Low	Low
Finnoff et al ²¹	Low	Low	Low	Low	High	Low	Low
Herbst et al ²⁷	Low	Low	Low	Low	Low	Low	Low
Hewett et al ³³	High	Low	Low	Low	High	Low	High
Khayambashi et al ³⁹	Low	Low	Low	Low	High	Low	Low
Leetun et al ⁴¹	Low	Low	Low	Low	High	Low	Low
Leppänen et al ⁴²	Low	High	High	Low	Low	Low	High
Luedke et al ⁴⁵	High	Low	Low	Low	High	Low	High
Noehren et al ⁵⁸	Low	Low	Low	Low	High	Low	Low
O'Kane et al ⁵⁹	Low	Low	High	Low	High	Low	High
Ramskov et al ⁶⁵	Low	Low	Low	Low	Low	Low	Low
Shimozaki et al ⁶⁸	Low	Low	Low	Low	Low	Low	Low
Steffen et al ⁷⁰	Low	Low	Low	Low	Low	Low	Low
Thijs et al ⁷²	Low	Low	Low	Low	High	Low	Low
Wilkerson et al ⁸⁰	Low	Low	Low	Low	High	High	High
Wilkerson and Colston ⁷⁹	Low	Low	Low	Low	High	High	High
Witvrouw et al ⁸²	Low	Low	Low	Low	High	High	High
Zazulak et al ⁸⁴	Low	Low	Low	Low	Low	Low	Low
Zazulak et al ⁸³	Low	Low	High	Low	Low	Low	Low

Abbreviation: QUIPS, Quality In Prognosis Studies.

^aItems: 1, Study participation; 2, Study attrition; 3, Prognostic factor measurement; 4, Outcome measurement; 5, Study confounding; 6, Statistical analysis and reporting.

[LITERATURE REVIEW]

TABLE 3

OUTCOME-LEVEL CERTAINTY ASSESSMENT (GRADE CRITERIA)

Hip Strength Outcome	Starting Score	Downgrading Factors ^a					Upgrading Factors ^b			Overall Credibility ^c
		1	2	3	4	5	1	2	3	
External rotation	2	-1	0	-1	-1	0	0	0	+1	0 (very low)
Internal rotation	2	-1	0	-1	-2	-1	0	0	+1	-2 (very low)
Extension	2	-1	0	-1	-1	-1	0	0	+1	-1 (very low)
Abduction	2	-1	-2	-1	-2	0	0	0	0	-4 (very low)

Abbreviations: GRADE, Grading of Recommendations Assessment, Development and Evaluation; QUIPS, Quality In Prognosis Studies.

^aItems: 1, Risk of bias: serious downgrade (-1) if 1 included study was considered to have a high risk of bias as assessed using the QUIPS tool, and very serious downgrade (-2) if 2 or more included studies were considered to have a high risk of bias as assessed using the QUIPS tool; 2, Inconsistency: serious downgrade (-1) if there was moderate heterogeneity (ie, $I^2 = 50\%-75\%$), and very serious downgrade (-2) if there was high heterogeneity ($I^2 > 75\%$); 3, Indirectness: serious downgrade (-1) if there were moderate differences between the populations, interventions, or outcomes measured across studies, and very serious downgrade (-2) if there were significant differences between the populations, interventions, or outcomes measured across studies; 4, Imprecision: serious downgrade (-1) if the confidence intervals were moderate (less than 0.5) and represented different conclusions, and very serious downgrade (-2) if the confidence intervals were large (greater than 1.0) and represented different conclusions; 5, Publication bias: serious downgrade (-1) if there was moderate publication bias, and very serious downgrade (-2) if there was significant publication bias.

^bItems: 1, Large effect: large upgrade (+1) if more than 50% of included studies had odds ratios greater than 2.0 or less than 0.5, and very large upgrade (+2) if more than 50% of included studies had odds ratios greater than 5.0 or less than 0.2; 2, Dose response: large upgrade (+1) if there was presence of a dose-response relationship; 3, All plausible residual confounding: large upgrade (+1) if, in greater than 75% of included studies, all plausible confounders unaccounted for in the adjusted analysis would reduce the demonstrated effect or increase the effect, if no effect was observed.

^cDerived from the sum of rating scores given for all GRADE criteria: 4 or greater is classified as high certainty, 3 is classified as moderate certainty, 2 is classified as low certainty, and 1 or less is classified as very low certainty.

not a risk factor for knee injuries,^{6,59} and 2 studies (both univariable analyses, 1 addressing confounding) found that greater hip abduction strength reduced the risk of knee injuries.^{45,65}

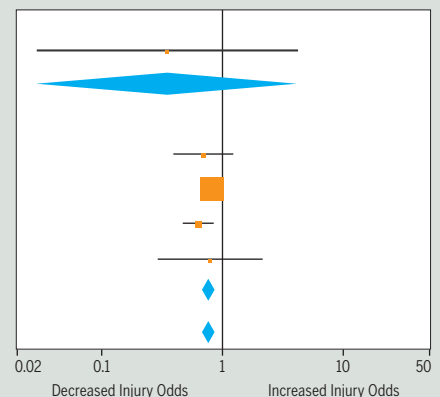
Other Hip Strength Variables Four studies investigated hip extension strength as a risk factor for athletic knee injuries.^{10,21,59,72} In a meta-analysis of 3 studies, there was very low–certainty evidence that hip extension strength was not a risk factor for future knee injuries (OR = 0.66; 95% CI: 0.42, 1.03; $P = .07$) (APPENDIX B).^{10,21,72} The study not included in the meta-analysis reported risk ratios, and supported the findings of the meta-analysis.⁵⁹ One study addressed confounding in a multivariable analysis.¹⁰

There was very low–certainty evidence in a meta-analysis of 3 studies that hip internal rotation strength was not a risk factor for knee injuries (OR = 0.92; 95% CI: 0.46, 1.84; $P = .82$) (APPENDIX B).^{10,21,72} One study addressed confounding in a multivariable analysis.¹⁰

Best-evidence synthesis suggested conflicting evidence (from 3 studies, none addressing confounding and 2 with low risk of bias) about whether hip flexion strength was a risk factor for athletic knee

Hip External Rotation Strength

Subgroup/Study	Log(OR) ± SE	Weight	OR IV, Random (95% Confidence Interval)
Eccentric strength			
Finnoff et al ²¹	-1.0498 ± 1.2708	0.2%	0.35 (0.03, 4.22)
Subtotal ^a		0.2%	0.35 (0.03, 4.22)
Isometric strength			
Boling et al ⁶⁰	-0.3653 ± 0.2914	3.8%	0.69 (0.39, 1.23)
Khayambashi et al ³⁹	-0.207 ± 0.0634	80.5%	0.81 (0.72, 0.92)
Leetun et al ⁴¹	-0.462 ± 0.1506	14.3%	0.63 (0.47, 0.85)
Thijs et al ⁷²	-0.2345 ± 0.5102	1.2%	0.79 (0.29, 2.15)
Subtotal ^a		99.8%	0.78 (0.70, 0.87)
Total ^a		100.0%	0.78 (0.70, 0.87)



Abbreviations: IV, inverse variance; OR, odds ratio; SE, standard error.

^aTest for overall effect: $z = 0.83$ ($P = .41$).

^bHeterogeneity: $\tau^2 = 0.00$, $\chi^2 = 2.60$, $df = 3$ ($P = .46$), $I^2 = 0\%$. Test for overall effect: $z = 4.39$ ($P < .001$).

^cHeterogeneity: $\tau^2 = 0.00$, $\chi^2 = 2.99$, $df = 4$ ($P = .56$), $I^2 = 0\%$. Test for overall effect: $z = 4.42$ ($P < .001$). Test for subgroup differences: $\chi^2 = 0.40$, $df = 1$ ($P = .53$), $I^2 = 0\%$.

FIGURE 2. Odds of knee injury with greater hip external rotation strength.

TABLE 4

CHARACTERISTICS OF INCLUDED STUDIES

Included Studies (n = 21)	Follow-up Period	Population	Exploratory Variable		Data Analysis	Injury Type and Definition ^a	
			Category/Method	Variable (Unit)		Type/Definition/Recording	Injuries, n
Bakken et al ⁶	2 playing seasons	n = 369 male (514 player-seasons; mean $\pm$ SD age, 26.0 $\pm$ 4.7 y) professional soccer players	Hip strength HHD	Eccentric hip adduction (Nm/kg) Eccentric hip abduction (Nm/kg) Isometric bilateral hip adduction squeeze (N/kg)	UV	Knee injuries Time loss Medical staff	70 legs
Boling et al ¹⁰	1-3 y	n = 1319 (806 male; age, 18-23 y) midshipmen from the US Naval Academy	Hip strength HHD	Isometric hip ER (kg; % BW) Isometric hip IR (kg; % BW) Isometric hip abduction (kg; % BW) Isometric hip extension (kg; % BW)	MV	PFPS Medical attention Medical staff	40 (16 male)
			Trunk/hip biomechanics 3-D motion analysis of single-leg drop jump	Peak hip flexion angle (deg) Peak hip adduction angle (deg) Peak hip IR angle (deg) Peak hip abduction moment (Nm) Peak hip ER moment (Nm)			
Dingenen et al ¹⁸	1 y	n = 50 (mean $\pm$ SD age: injured, 20.2 $\pm$ 2.9 y; noninjured, 20.8 $\pm$ 3.5 y) elite female soccer, handball, and volleyball athletes	Trunk/hip biomechanics 2-D motion analysis of single-leg drop jump	Peak hip flexion angle (deg) Peak KVLTM angle (deg)	UV and CF	Noncontact knee injuries Time loss Medical staff	7
Finnoff et al ²¹	2 y	n = 98 (53 male; mean age: injured, 15.6 y; noninjured, 15.97 y) high school running athletes	Hip strength HHD	Eccentric hip flexion (Nm) Eccentric hip extension (Nm) Eccentric hip IR (Nm) Eccentric hip ER (Nm) Eccentric hip abduction (Nm) Eccentric hip adduction (Nm)	UV	PFPS Medical attention Medical staff	5 (2 male)
Herbst et al ²⁷	1 y	n = 255 female (mean age: injured, 12.7 y; noninjured, 12.8 y) middle school basketball athletes	Hip strength Isokinetic dynamometer at 120°/s	Isokinetic hip abduction (Nm/kg)	UV and CF	PFPS Medical attention Medical staff	38
Hewett et al ³³	1-2 playing seasons	n = 205 female (mean $\pm$ SD age: injured, 15.8 $\pm$ 1.0 y; noninjured, 16.1 $\pm$ 1.7 y) soccer, basketball, and volleyball athletes	Trunk/hip biomechanics 3-D motion analysis of bilateral-leg drop jump	Peak stance hip adduction moment (Nm) Peak external hip flexion moment (Nm)	UV	Noncontact ACL injuries Medical attention Medical staff	9
Khayambashi et al ³⁹	1 playing season	n = 468 (333 male; mean $\pm$ SD age: injured, 21.8 $\pm$ 4.2 y; noninjured, 21.3 $\pm$ 5.2 y) competitive athletes (futsal, soccer, volleyball, basketball, handball)	Hip strength HHD	Isometric hip abduction (kg; % BW) Isometric hip ER (kg; % BW)	UV	Noncontact ACL injuries Medical attention Medical staff	15 (9 male)
Leetun et al ^{41b}	1 playing season	n = 139 (80 male; mean $\pm$ SD age: male, 19.1 $\pm$ 1.37 y; female, 19.0 $\pm$ 0.90 y) collegiate basketball and track athletes	Hip strength HHD Trunk strength and control Various clinical tests	Isometric hip ER (kg; % BW) Isometric hip abduction (kg; % BW) Biering-Sørensen test (s) Sidebridge hold (s)	UV	Knee injuries Time loss Medical staff	6 (1 male)

Table continues on page 482

TABLE 4

CHARACTERISTICS OF INCLUDED STUDIES (CONTINUED)

Included Studies (n = 21)	Follow-up Period	Population	Exploratory Variable		Data Analysis	Injury Type and Definition ^a	
			Category/Method	Variable (Unit)		Type/Definition/Recording	Injuries, n
Leppänen et al ⁴²	1-3 y	n = 171 (mean ± SD age: basketball, 14.6 ± 1.6 y; floorball, 16.5 ± 1.8 y) junior female basketball and floorball athletes	Trunk/hip biomechanics 3-D motion analysis of bilateral-leg drop jump	Hip flexion range of motion (deg) Peak external hip flexion moment (Nm)	MV	Noncontact ACL injuries Medical attention Medical staff	15 legs
Luedke et al ⁴⁵	1 playing season	n = 68 (21 male; mean ± SD age, 16.2 ± 1.3 y) high school cross-country runners	Hip strength HHD	Isometric hip abduction (Nm/kg)	UV	Anterior knee pain Time loss Coach and medical staff	3 (1 male)
Noehren et al ⁵⁸	2 y	n = 400 female (mean ± SD age, 27 ± 10 y) novice runners	Trunk/hip biomechanics 3-D motion analysis of running motion	Peak stance hip adduction angle (deg) Peak stance hip IR angle (deg)	UV	PFPS Medical attention Medical staff	15
O'Kane et al ⁵⁹	1-2 playing seasons	n = 351 female (age, 12-15 y) youth soccer players	Hip strength HHD	Eccentric hip flexion (Nm) Eccentric hip extension (Nm) Eccentric hip abduction (Nm) Eccentric hip adduction (Nm) Eccentric hip ER (Nm)	UV	Knee overuse injuries Medical attention Self-reporting and medical staff	38
Ramkov et al ⁶⁵	1 y	n = 629 (321 male; mean ± SD age: male, 36.6 ± 10.1 y; female, 19.0 ± 0.90 y) novice runners	Hip strength HHD	Eccentric hip abduction (Nm/kg)	MV	PFPS Medical attention Medical staff	24 (11 male)
Shimozaki et al ⁶⁸	3 playing seasons	n = 171 female (mean ± SD age: injured, 185.2 ± 3.8 mo; uninjured, 185.5 ± 3.5 mo) high school basketball players	Hip strength HHD	Isometric hip abduction (Nm/kg)	UV and CF	Noncontact ACL injuries Medical attention Medical staff	12
Steffen et al ⁷⁰	1-8 y	n = 867 female (mean ± SD age, 20.9 ± 4.0 y) elite handball and football players	Hip strength HHD	Isometric hip abduction (kg)	MV	Noncontact ACL injuries Medical attention Medical staff	57
Thijs et al ⁷²	10 wk	n = 77 female (mean ± SD age, 38 ± 9 y) novice recreational runners	Hip strength HHD	Isometric hip flexion (N/kg) Isometric hip extension (N/kg) Isometric hip abduction (N/kg) Isometric hip adduction (N/kg) Isometric hip IR (N/kg) Isometric hip ER (N/kg)	UV	PFPS Time loss Medical staff	16
Wilkerson et al ^{80bc}	1 playing season	n = 83 male (mean ± SD age, 20 ± 1.5 y) collegiate football players	Trunk strength and control Various clinical tests	Sidebridge hold (s)	UV	Knee injuries Time loss Medical staff	8
Wilkerson and Colston ^{79bc}	3 playing seasons	n = 152 male (mean ± SD age, 19.7 ± 1.5 y) collegiate football players	Trunk strength and control Various clinical tests	Trunk flexion hold (s) Modified Biering-Sørensen test (s)	UV	Knee injuries Time loss Medical staff	20
Witvrouw et al ⁸²	2 y	n = 282 (151 male; age, 18.6 y [range, 17-21 y]) physical education university students	Trunk strength and control Various clinical tests	Sit-ups (repetitions, n)	UV	PFPS Medical attention Medical staff	24 (11 male)
Zazulak et al ⁸⁴	3 y	n = 277 (140 male; mean ± SD age: male, 19.4 ± 1.0 y; female, 19.3 ± 1.8 y) collegiate athletes	Trunk strength and control Various clinical tests	Active proprioceptive repositioning and passive proprioceptive repositioning measured in terms of absolute error (deg)	UV and CF	Knee injuries Medical attention Medical staff	25 (14 male)

Table continues on page 483.

TABLE 4

CHARACTERISTICS OF INCLUDED STUDIES (CONTINUED)

Included Studies (n = 21)	Follow-up Period	Population	Exploratory Variable		Data Analysis	Injury Type and Definition ^a	
			Category/Method	Variable (Unit)		Type/Definition/Recording	Injuries, n
Zazulak et al ⁸³	3 y	n = 277 (140 male; mean $\pm$ SD age: male, 19.4 $\pm$ 1.0 y; female, 19.3 $\pm$ 1.8 y) collegiate athletes	Trunk strength and control Various clinical tests	Angular displacement of the trunk in lateral flexion, extension, and flexion following a sudden force release (deg)	UV and CF	Knee injuries Medical attention Medical staff	25 (14 male)

Abbreviations: ACL, anterior cruciate ligament; BW, body weight; CF, addressed confounding (age, sex, previous history of knee injuries); ER, external rotation; HHD, handheld dynamometer; IR, internal rotation; KVLTM, knee valgus plus ipsilateral lateral trunk motion; MV, multivariable analysis; PFPS, patellofemoral pain syndrome; UV, univariable analysis.

^aAccording to Fuller et al²² and Clarsen and Bahr.¹⁴

^bData were obtained from authors directly and were not available in the published manuscript; odds ratios were calculated using univariate logistic regression.

^cThere was an overlap of data between Wilkerson and Colston⁷⁹ and Wilkerson et al,⁸⁰ which was resolved following direction from the original authors.

injuries,^{21,59,72} and strong evidence (from 4 studies that did not address confounding, 2 with low risk of bias) to suggest that hip adduction strength was not a risk factor for athletic knee injuries (see **TABLE 5**).^{6,21,59,72}

Trunk and Hip Biomechanics

Seven variables relating to trunk and hip biomechanics across 5 studies were assessed in a best-evidence synthesis (**TABLE 5**). There was limited evidence (from 1 study that addressed confounding and had low risk of bias) to suggest that a combination of increased peak knee valgus and ipsilateral trunk angle when landing unilaterally from a jump predicted noncontact knee injuries.¹⁸ There was conflicting evidence about whether hip flexion angle (from 3 studies, all addressing confounding and 2 with low risk of bias),^{10,18,42} hip adduction angle (from 2 studies, 1 addressing confounding and 2 with low risk of bias),^{10,58} and hip internal rotation angle (from 2 studies with low risk of bias, 1 addressing confounding)^{10,58} were risk factors for athletic knee injuries. There was limited to moderate evidence suggesting that hip flexion moment (from 2 studies with high risk of bias, 1 addressing confounding)^{33,42} and external rotation and abduction moments (from 1 study that addressed confounding and had low risk of bias)¹⁰ were not risk factors for knee injuries.

Trunk Strength and Control Six variables relating to trunk strength and control across 6 studies were assessed in a best-evidence synthesis (**TABLE 5**). There was limited evidence (from 2 studies that addressed confounding and had low risk of bias) from the same participant cohort to suggest that impaired core proprioception, as assessed by active proprioceptive repositioning of the trunk,⁸⁴ and deficits in neuromuscular control, as assessed by greater lateral trunk displacement after a sudden force release,⁸³ were risk factors for knee injuries. There was limited to moderate evidence suggesting that performances on the modified Biering-Sørensen endurance (from 2 studies, both addressing confounding and 1 with low risk of bias),^{41,79} sidebridge (from 2 studies, none addressing confounding and 1 with low risk of bias),^{41,80} trunk flexion hold (from 1 study that did not address confounding and had high risk of bias),⁷⁹ and sit-up tests (from 1 study that did not address confounding and had high risk of bias)⁸² were not risk factors for future athletic knee injuries.

DISCUSSION

THE PRIMARY AIM OF THIS REVIEW was to determine whether neuromuscular deficits in trunk and hip-related function were risk factors for future knee injuries in athletic popu-

lations. There was very low-certainty evidence from meta-analysis that greater hip external rotation strength was protective against athletic knee injuries. There was limited evidence from single studies that deficits in trunk proprioception and neuromuscular control, and the combination of excessive knee valgus and ipsilateral trunk angle, may be risk factors for sustaining athletic knee injuries.

Strong hip abductors, extensors, and external rotators may be associated with reduced risk of knee injury, as they help to control knee valgus motion during high-speed cutting, jumping, and landing movements.^{20,32,47,48,64,66} However, only external rotation strength was associated with lower odds of athletic knee injuries in this review. The relationship between hip abduction strength and knee injuries is unclear. While some studies have reported that hip abduction strength is not a risk factor for knee injuries,^{6,41,59,70,72} others are split as to whether greater^{10,39,45,65} or lower^{21,27,68} hip abduction strength is more protective of risk of athletic knee injuries. This conflict in findings may be partially explained by the substantial variation in hip abduction strength testing and recording methods employed across the included studies. For example, participant testing positions varied between supine and sidelying,^{70,72} rest periods between measurements lasted anywhere from 15 to 120 seconds,^{41,68} and

[LITERATURE REVIEW]

TABLE 5

BEST-EVIDENCE SYNTHESIS

		Univariable		Multivariable		Association With Risk ^a			Best-Evidence Synthesis	
Variable	n	Low Risk of Bias	High Risk of Bias	Low Risk of Bias	High Risk of Bias	↑	↓	=	Presence of Association	Level of Evidence
Hip Strength										
Adduction										
Isometric	77								No	Strong
Thijs et al ⁷²		X						X		
Isometric (bilateral) squeeze	369								No	Strong
Bakken et al ⁶			X					X		
Eccentric	818								No	Strong
Bakken et al ⁶			X					X		
Finnoff et al ²¹		X						X		
O'Kane et al ⁵⁹			X					X		
Flexion										
Isometric	77								No	Conflicting
Thijs et al ⁷²		X						X		
Eccentric	449								Unknown	Conflicting
Finnoff et al ²¹		X						X		
O'Kane et al ⁵⁹			X				X			
Trunk and Hip Biomechanics										
Hip flexion angle (peak)										
Single-leg drop jump	1369								No	Conflicting
Boling et al ¹⁰				X				X		
Dingenen et al ¹⁸		X						X		
Bilateral drop jump	171								Yes	Conflicting
Leppänen et al ⁴²					X		X			
Hip adduction angle (peak)										
Single-leg drop jump	1319								No	Conflicting
Boling et al ¹⁰				X				X		
Running stance	400								Yes	Conflicting
Noehren et al ⁵⁸		X				X				
Knee valgus and lateral trunk angle (peak)	50								Yes	Limited
Dingenen et al ¹⁸		X				X				
Hip internal rotation angle (peak)										
Single-leg drop jump	1319								Yes	Conflicting
Boling et al ¹⁰				X		X				
Running stance	400								No	Conflicting
Noehren et al ⁵⁸		X						X		
Hip flexion moment										
Hewett et al ³³	376		X					X	No	Moderate
Leppänen et al ⁴²					X			X		
Hip external rotation moment										
Boling et al ¹⁰	1319			X				X	No	Limited
Hip abduction moment										
Boling et al ¹⁰	1319			X				X	No	Limited

Table continues on page 485.

TABLE 5

BEST-EVIDENCE SYNTHESIS (CONTINUED)

		Univariable		Multivariable		Association With Risk ^a			Best-Evidence Synthesis	
Variable	n	Low Risk of Bias	High Risk of Bias	Low Risk of Bias	High Risk of Bias	↑	↓	=	Presence of Association	Level of Evidence
Trunk Strength/Control										
Modified Biering-Sørensen test	291								No	Moderate
Leetun et al ⁴¹		X						X		
Wilkerson and Colston ⁷⁹			X					X		
Sidebridge test	222								No	Moderate
Leetun et al ⁴¹		X						X		
Wilkerson et al ⁸⁰			X					X		
Trunk flexion hold	152								No	Limited
Wilkerson and Colston ⁷⁹			X					X		
Sit-ups	282								No	Limited
Witvrouw et al ⁸²			X					X		
Active proprioceptive repositioning error	277								Yes	Limited
Zazulak et al ⁸⁴		X				X				
Lateral trunk displacement after sudden force release	277								Yes	Limited
Zazulak et al ⁸³		X				X				
^a ↑, Increase in variable is associated with greater risk of future knee injury; ↓, Decrease in variable is associated with lower risk of future knee injury; =, No significant association between variable and future knee injury risk.										

normalization methods varied. Standardizing data-collection procedures would help to ensure that findings are comparable between studies and to discern the role of hip strength in athletic knee injury etiology.

Deficits in trunk control have been linked to athletic knee injuries^{30,32,34,48,64} but prospectively investigated in only 2 cohorts.^{18,83} Zazulak et al⁸³ assessed lateral trunk displacement after a sudden force release while semi-seated in a novel apparatus, while Dingenen et al¹⁸ measured knee valgus and ipsilateral trunk angles when landing unilaterally from a jump, using 2-D video analysis. Although both studies reported that deficits in trunk control were risk factors for sustaining athletic knee injuries, interpreting these findings requires caution, because the clinimetrics of their assessment methods have not been fully established. Recently, technology such as wearable inertial measurement units has emerged as a promising clinical assessment alternative to gold standard, laboratory-based, opto-

electronic 3-D motion-analysis methods to assess frontal plane movement.^{8,12} Accessible and valid assessment tools may aid more widespread efforts to better understand the causal relationship between frontal plane trunk movement and athletic knee injuries.

Most other variables related to trunk and hip neuromuscular function were not risk factors for future athletic knee injuries. This finding raises important questions about the relevance of one-off trunk and hip function screening (eg, preseason screening) and exercise-based interventions to reduce injury risk. On the one hand, it is plausible that these variables are not risk factors and should not be the focus of screening and intervention efforts; on the other hand, a dearth of published research and methodological weaknesses (eg, insufficiently powered studies, the absence of complex-systems approaches to study the multifactorial nature of injuries in athletes,^{4,9,11} and nonuniform injury definitions^{4,14}) suggest that current findings should be interpret-

ed with caution. Therefore, even though the majority of variables relating to trunk and hip neuromuscular function were not risk factors for athletic knee injuries, it is possible that these findings may change with methodologies designed to assess causal relationships.^{28,29}

Implications for Practice

Identifying modifiable risk factors remains a prime concern in the effort to reduce knee injury risk in athletes. While there may be some value in assessing and improving hip external rotation strength, trunk proprioception and neuromuscular control, and the combination of knee valgus and ipsilateral trunk control, most other trunk and hip-related variables were not predictive of future knee injury. There is support for the inclusion of trunk- and hip-focused components in exercise-based knee injury risk reduction programs,^{19,71} but it is uncertain whether additional emphasis on these components would result in greater injury risk reduction. Practitioners may consider

other factors, like organizational contexts (eg, training phase, competition type/level, stakeholder demands)^{2,23} and individual variability (eg, biomechanical risk profiles, knee injury history),^{31,51,60} that influence decision making.

Limitations

A lack of standardization of assessment methods and a dearth of studies reporting on the same variable restricted the analysis of most variables in a best-evidence synthesis. Although a thorough search of 6 online databases and a bibliographic hand search of included studies were performed, relevant studies may have been missed by not tracking citations and searching gray literature. For pragmatic reasons, the OR was used as an effect measure in the quantitative syntheses. Conclusions solely from relative measures of association like the OR require caution, because they do not consider minimally important differences in injury risk and therefore limit interpretability.⁵⁵ An argument could be made against pooling different hip strength measurement methods (isokinetic, isometric, eccentric) in the same meta-analysis. Despite the absence of standardized strength assessment methods, pooling these measures is supported by evidence reporting moderate to high correlations between all 3 measurement methods.^{50,78} Additional methodological efforts to account for pooling these measures were GRADE downgrading and random-effects methods.^{50,78}

Future Research Directions

Future research should consider the interconnected, multidirectional, and evolving patterns of interaction between risk factors and the emerging pattern (athletic injury). This may be achieved by (1) employing intensive longitudinal methods to scrutinize the relationship between the course of change of risk factors and injury outcomes,^{55,56,81} and (2) complementing current reductionist approaches in athletic injury control research with more complex, ecological ap-

proaches like agent-based modeling and classification and regression trees.^{9,36,57}

CONCLUSION

MOST VARIABLES OF TRUNK AND HIP function were not risk factors for injuries. Further research is required to confirm whether hip external rotation strength, trunk proprioception and neuromuscular control, and the combination of knee valgus angle and ipsilateral trunk control are risk factors for future knee injuries. ●

KEY POINTS

FINDINGS: There was very low-certainty and limited evidence that reduced hip external rotation strength, deficits in trunk proprioception and neuromuscular control, and the combination of excessive knee valgus and ipsilateral trunk angle may be risk factors for knee injury. Most other variables relating to trunk and hip neuromuscular function were not risk factors for knee injuries.

IMPLICATIONS: Several clinical and laboratory-based measures of trunk and hip strength, control, and biomechanics exist, but most are of limited value when used as a one-off screening test; further research is required to confirm whether they are risk factors for athletic knee injuries. Current evidence is unable to corroborate whether additional emphasis on trunk and hip-related components that are already part of a well-rounded exercise-based injury risk reduction program would further reduce knee injury risk.

CAUTION: The certainty of evidence, methodological weaknesses of included studies, and the dearth of published research suggest that current findings should be interpreted with caution.

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors contributed to project conception, project planning, and interpretation of data. Lionel Chia and Dr de Oliveira Silva conducted the literature search, record

screening, methodological appraisal, and data extraction and synthesis. Lionel Chia drafted the initial manuscript, which was critically revised and approved for submission by all authors.

DATA SHARING: Raw data from data analysis are available on reasonable request by contacting the corresponding author. The data are not publicly available because some data were obtained directly from authors of the included studies, and subsequent ethical approval would have to be sought from these respective authors.

PATIENT AND PUBLIC INVOLVEMENT: Patients or public partners were not involved in the design, conduct, or interpretation of this systematic review.

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13. propriocepti*.mp. or Proprioception/ (14017)
14. control.mp. (3657766)
15. Physical Endurance/ or endurance.mp. (36103)
16. force.mp. (241718)
17. power.mp. (303135)
18. torque.mp. (22075)
19. kinematic*.mp. (32651)
20. kinetic*.mp. (690528)
21. activation*.mp. (1114778)
22. 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 (6167077)
23. risk reduction behavio\$r/ (11401)
24. risk reduction.mp. (27100)
25. predict*.mp. (1505442)
26. prevent*.mp. (2213458)
27. association.mp. (1066138)
28. prophyla*.mp. (167335)
29. 23 or 24 or 25 or 26 or 27 or 28 (4520389)
30. Knee/ or Knee Joint/ or knee.mp. (152806)
31. Patellofemoral Joint/ or Patella/ or patell*.mp. or Patellar Ligament/ (24409)
32. (anterior cruciate ligament or posterior cruciate ligament).mp. or anterior cruciate ligament/ (21822)
33. Menisci, Tibial/ or Tibial Meniscus Injuries/ or menisc*.mp. (16921)
34. quadricep*.mp. (16518)
35. iliotibial band.mp. (753)
36. tibi?femoral or tibi?-femoral).mp. (3140)
37. 30 or 31 or 32 or 33 or 34 or 35 or 36 (179303)
38. injur*.mp. or "Wounds and Injuries"/ (1125318)
39. "Sprains and Strains"/ or Athletic Injuries/ or sprain*.mp. (32557)
40. tear*.mp. (48377)
41. pain*.mp. (721373)
42. tend?n*.mp. (205019)
43. syndrome.mp. (1107343)
44. 38 or 39 or 40 or 41 or 42 or 43 (2941190)
45. Sport*.mp. or Sports/ (94510)
46. Athletes/ or Athletic Performance/ or athlet*.mp. or player*.mp. (120103)
47. (runn* or sprint*).mp. (70085)
48. Dancing/ or danc*.mp. (7356)

APPENDIX A

49. Military Personnel/ or militar*.mp. or soldier*.mp. (89377)
50. 45 or 46 or 47 or 48 or 49 (320011)
51. 10 and 22 and 29 and 37 and 44 and 50 (743)

Embase (1947-1973, 1974-April 12, 2019)

1. trunk.mp. or Torso/ (84984)
2. core.mp. (315428)
3. Spine/ or spine.mp. or spinal.mp. (591986)
4. back musc*.mp. or Back Muscles/ (3850)
5. Pelvis/ or lumbo-pelvic.mp. or lumbopelvic.mp. (61041)
6. Proximal.mp. (276272)
7. Hip Joint/ or Hip/ or hip.mp. (212320)
8. groin.mp. or Groin/ or adduct*.mp. or abduct*.mp. (113741)
9. glute*.mp. (35847)
10. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 (1576089)
11. stability.mp. (534583)
12. strength*.mp. or Muscle Strength/ (495896)
13. propriocepti*.mp. or Proprioception/ (19757)
14. control.mp. (3672306)
15. Physical Endurance/ or endurance.mp. (43640)
16. force.mp. (281259)
17. power.mp. (349469)
18. torque.mp. (25196)
19. kinematic*.mp. (42524)
20. kinetic*.mp. (591051)
21. activation*.mp. (1389009)
22. 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 (6566989)
23. risk reduction behavio\$#/ (87249)
24. risk reduction.mp. (104770)
25. predict*.mp. (1989260)
26. prevent*.mp. (2654076)
27. association.mp. (2118423)
28. prophyla*.mp. (303497)
29. 23 or 24 or 25 or 26 or 27 or 28 (6321307)
30. Knee/ or Knee Joint/ or knee.mp. (219437)
31. Patellofemoral Joint/ or Patella/ or patell*.mp. or Patellar Ligament/ (33143)
32. (anterior cruciate ligament or posterior cruciate ligament).mp. or anterior cruciate ligament/ (27917)
33. Menisci, Tibial/ or Tibial Meniscus Injuries/ or menisc*.mp. (23891)
34. quadricep*.mp. (23989)
35. iliotibial band.mp. (1040)
36. (tibi?femoral or tibi?-femoral).mp. (4571)
37. 30 or 31 or 32 or 33 or 34 or 35 or 36 (251479)
38. injur*.mp. or "Wounds and Injuries"/ (1584207)
39. "Sprains and Strains"/ or Athletic Injuries/ or sprain*.mp. (254225)
40. tear*.mp. (68045)
41. pain*.mp. (1278885)
42. tend?n*.mp. (299042)
43. syndrome.mp. (1785666)
44. 38 or 39 or 40 or 41 or 42 or 43 (4497084)
45. Sport*.mp. or Sports/ (135644)
46. Athletes/ or Athletic Performance/ or athlet*.mp. or player*.mp. (136739)
47. (runn* or sprint*).mp. (92717)

APPENDIX A

48. Dancing/ or danc*.mp. (9831)
 49. Military Personnel/ or militar*.mp. or soldier*.mp. (86046)
 50. 45 or 46 or 47 or 48 or 49 (386661)
 51. 10 and 22 and 29 and 37 and 44 and 50 (947)

SPORTDiscus

	Query ^a	Limiters/Expanders	Results
S1	trunk OR core OR spine OR spinal OR lumbopelvic OR lumbopelvic OR lumbar OR back OR proximal OR hip OR femoro-acetabular OR femoroacetabular OR groin OR abduct* OR adduct* OR glute*	Search modes: Boolean/phrase	120717
S2	Strength OR stability OR propriocept* OR control OR endurance OR force OR power OR torque OR kinematic* OR kinetic* OR activation*	Search modes: Boolean/phrase	295462
S3	risk reduction OR predict* OR prevent* OR prophyla* OR association	Search modes: Boolean/phrase	361144
S4	injur* OR tear* OR sprain* OR strain* OR pain* OR tend?n* OR syndrome	Search modes: Boolean/phrase	223578
S5	sport* OR athlet* OR player* OR danc* OR militar* OR soldier*	Search modes: Boolean/phrase	1193701
S6	knee OR patell* OR (anterior cruciate ligament or acl) OR (posterior cruciate ligament or pcl) OR tibiofemoral OR tibiofemoral OR menisc* OR iliotibial band OR quadricep*	Search modes: Boolean/phrase	53701
S7	S1 AND S2 AND S3 AND S4 AND S5 AND S6	Limiters: peer reviewed, publication type: academic journal, search modes: Boolean/phrase	791

^aLast run via: interface, EBSCOhost Research Databases; search screen, advanced search; database, SPORTDiscus with Full Text.

Web of Science

TS=(trunk OR core OR spine OR spinal OR lumbo-pelvic OR lumbopelvic OR lumbar OR back OR proximal OR hip OR groin OR adduct* OR abduct* OR glute*) AND TS=(stability OR strength OR propriocept* OR control OR endurance OR force OR power OR torque OR kinematic* OR kinetic* OR activation*) AND TS=(“risk reduction” OR predict* OR prevent* OR prophyla* OR association) AND TS=(knee* OR patell* OR tibiofemoral OR tibio-femoral OR quadricep* OR “iliotibial band” OR menisc* OR “anterior cruciate ligament” OR “posterior cruciate ligament”) AND TS=(injur* OR sprain* OR strain* OR tear* OR pain* OR tend*) AND TS=(sport* OR athlet* OR player* OR danc* OR runn* OR sprint* OR militar* or soldier*)

Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCII-S, CPCII-SSH, ESCI, CCR-EXPANDED, IC Timespan=All years

Scopus

(TITLE-ABS-KEY (trunk OR core OR spine OR spinal OR lumbo-pelvic OR lumbopelvic OR lumbar OR back OR proximal OR hip OR groin OR adduct* OR abduct* OR glute*)) AND (TITLE-ABS-KEY (stability OR strength OR propriocept* OR control OR endurance OR force OR power OR torque OR kinematic* OR kinetic* OR activation*)) AND (TITLE-ABS-KEY (“risk reduction” OR predict* OR prevent* OR prophyla* OR association)) AND (TITLE-ABS-KEY (knee* OR patell* OR tibiofemoral OR tibio-femoral OR quadricep* OR “iliotibial band” OR menisc* OR “anterior cruciate ligament” OR “posterior cruciate ligament”)) AND (TITLE-ABS-KEY (injur* OR sprain* OR strain* OR tear* OR pain* OR tend?n* OR syndrome)) AND (TITLE-ABS-KEY (sport* OR athlet* OR player* OR danc* OR runn* OR sprint* OR militar* OR soldier*)) AND DOCTYPE (ar OR re)

CINAHL

	Query ^a	Results
S43	S11 AND S21 AND S24 AND S30 AND S34 AND S42	466
S42	S35 OR S36 OR S37 OR S38 OR S39 OR S40 OR S41	72766
S41	(MH “Knee”) OR “knee” OR (MH “Knee Joint+”)	62934
S40	“tibi?femoral” OR “tibiofemoral”	1365
S39	(MH “Iliotibial Band”) OR “iliotibial band”	508
S38	(MH “Quadriceps Muscles+”) OR “quadricep”	7492
S37	(MH “Meniscal Injuries”) OR “menisc”	4972
S36	(MH “Anterior Cruciate Ligament”) OR “anterior cruciate ligament” OR (MH “Posterior Cruciate Ligament”)	11245
S35	(MH “Patella”) OR (MH “Patellar Ligament”) OR “patell”	8483
S34	S31 OR S32 OR S33	150868
S33	“danc” OR (MH “Dancing+”)	5392
S32	(MH “Military Personnel”) OR (MH “Military Services”) OR (MH “Military Recruits”) OR (MH “Research, Military”) OR “military”	29518

Table continues on page A4.

[LITERATURE REVIEW]

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	Query*	Results
S31	(MH "Sports+") OR "sport*" OR "player*" OR "athlet*" OR (MH "Athletes+")	118504
S30	S25 OR S26 OR S27 OR S28 OR S29	917744
S29	(MH "Tendon Injuries+") OR (MH "Tendinopathy+") OR (MH "Musculoskeletal Diseases+") OR "tend? n"	252946
S28	(MH "Pain+") OR "pain"	287164
S27	"syndrome" OR (MH "Syndrome")	203665
S26	(MH "Sprains and Strains+") OR "sprain*" OR "tear"	23882
S25	"injur*" OR (MH "Wounds and Injuries+")	351746
S24	S22 OR S23	1216057
S23	"predict*" OR "prevent*" OR "prophyla*" OR "association"	1213924
S22	(MH "Risk for Injury (NANDA)+") OR "risk reduction"	7042
S21	S12 OR S13 OR S14 OR S15 OR S16 OR S17 OR S18 OR S19 OR S20	1073063
S20	"activation"	55098
S19	"kinematic*" OR (MH "Kinematics") OR (MH "Kinetics") OR "kinetic"	27452
S18	(MH "Torque") OR "torque"	7518
S17	"power" OR "force"	103585
S16	"stability"	30495
S15	(MH "Physical Endurance+") OR "endurance"	17882
S14	"control"	863704
S13	"propriocept*" OR (MH "Proprioception+")	4686
S12	(MH "Muscle Strength+") OR "strength"	62477
S11	S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7 OR S8 OR S9 OR S10	152870
S10	"adduct*" OR "abduct"	9519
S9	(MH "Groin") OR "groin"	2735
S8	"glute"	6036
S7	(MH "Hip Injuries+") OR (MH "Hip") OR (MH "Hip Joint")	22535
S6	"proximal"	23361
S5	"lumbo-pelvic"	171
S4	"lumbopelvic"	520
S3	(MH "Spine+") OR "spine"	52978
S2	"core"	35884
S1	(MH "Torso") OR "trunk"	10585

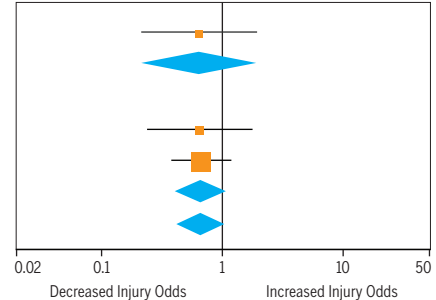
*Limiters, peer reviewed; search modes, Boolean/phrase. Last run via: interface, EBSCOhost Research Databases; search screen, advanced search; database, CINAHL.

APPENDIX B

META-ANALYSES FOR HIP STRENGTH

Hip Extension Strength

Subgroup/Study	Log(Odds Ratio) $\pm$ SE	Weight	Odds Ratio IV, Random (95% Confidence Interval)
Eccentric strength			
Finnoff et al ²¹	-0.4463 $\pm$ 0.5613	16.9%	0.64 (0.21, 1.92)
Subtotal ^a		16.9%	0.64 (0.21, 1.92)
Isometric strength			
Thijs et al ⁷²	-0.4339 $\pm$ 0.511	20.4%	0.65 (0.24, 1.76)
Boling et al ¹⁰	-0.405 $\pm$ 0.2911	62.8%	0.67 (0.38, 1.18)
Subtotal ^b		83.1%	0.66 (0.40, 1.09)
Total ^c		100.0%	0.66 (0.42, 1.03)



Abbreviations: IV, inverse variance; SE, standard error.

^aTest for overall effect: $z = 0.80$ ($P = .43$).

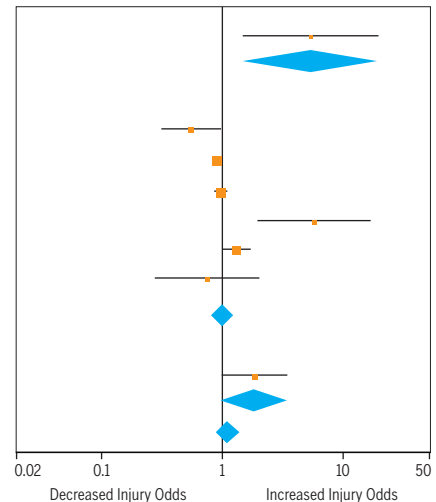
^bHeterogeneity: $\tau^2 = 0.00$, $\chi^2 = 0.00$, $df = 1$ ($P = .96$), $I^2 = 0\%$. Test for overall effect: $z = 1.63$ ($P = .10$).

^cHeterogeneity: $\tau^2 = 0.00$, $\chi^2 = 0.01$, $df = 2$ ($P = 1.00$), $I^2 = 0\%$. Test for overall effect: $z = 1.81$ ($P = .07$). Test for subgroup differences: $\chi^2 = 0.00$, $df = 1$ ($P = .96$), $I^2 = 0\%$.

FIGURE 1. Odds of knee injury with greater hip extension strength.

Hip Abduction Strength

Subgroup/Study	Log(Odds Ratio) $\pm$ SE	Weight	Odds Ratio IV, Random (95% Confidence Interval)
Eccentric strength			
Finnoff et al ²¹	1.6771 $\pm$ 0.662	2.8%	5.35 (1.46, 19.58)
Subtotal ^a		2.8%	5.35 (1.46, 19.58)
Isometric strength			
Boling et al ¹⁰	-0.6051 $\pm$ 0.291	10.1%	0.55 (0.31, 0.97)
Khayambashi et al ³⁹	-0.1133 $\pm$ 0.034	26.0%	0.89 (0.84, 0.95)
Leetun et al ⁴¹	-0.04 $\pm$ 0.064	24.6%	0.96 (0.85, 1.09)
Shimozaki et al ⁶⁸	1.743 $\pm$ 0.552	3.8%	5.71 (1.94, 16.86)
Steffen et al ⁷⁰	0.262 $\pm$ 0.138	19.4%	1.30 (0.99, 1.70)
Thijs et al ⁷²	-0.302 $\pm$ 0.51	4.4%	0.74 (0.27, 2.01)
Subtotal ^b		88.3%	1.00 (0.81, 1.23)
Isokinetic strength			
Herbst et al ²⁷	0.6049 $\pm$ 0.32	8.9%	1.83 (0.98, 3.43)
Subtotal ^c		8.9%	1.83 (0.98, 3.43)
Total ^d		100.0%	1.11 (0.88, 1.40)



Abbreviations: IV, inverse variance; SE, standard error.

^aTest for overall effect: $z = 2.53$ ($P = .01$).

^bHeterogeneity: $\tau^2 = 0.03$, $\chi^2 = 21.84$, $df = 5$ ($P = .0006$), $I^2 = 77\%$. Test for overall effect: $z = 0.03$ ($P = .97$).

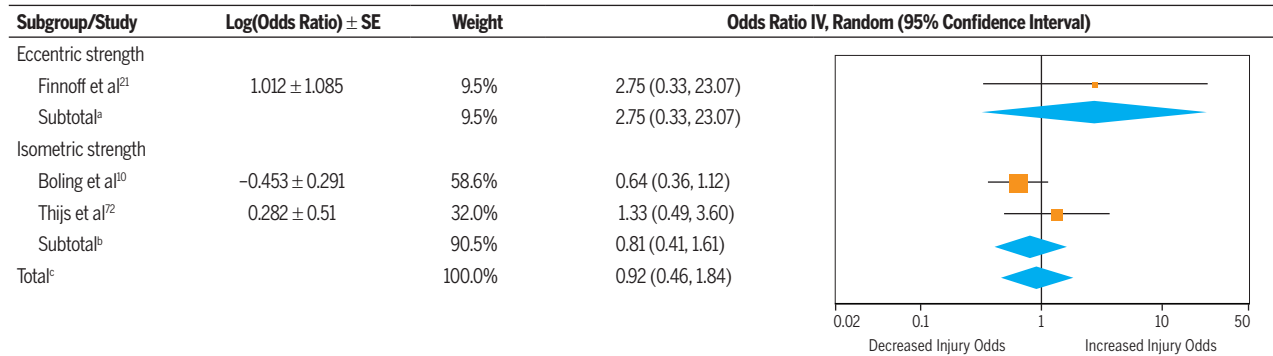
^cTest for overall effect: $z = 1.89$ ($P = .06$).

^dHeterogeneity: $\tau^2 = 0.05$, $\chi^2 = 33.41$, $df = 7$ ($P < .0001$), $I^2 = 79\%$. Test for overall effect: $z = 0.90$ ($P = .37$). Test for subgroup differences: $\chi^2 = 9.11$, $df = 2$ ($P = .01$), $I^2 = 78\%$.

FIGURE 2. Odds of knee injury with greater hip abduction strength. For the study by Shimozaki et al,⁶⁸ odds ratios were computed from between-group differences and were not identical to binary logistic regression analysis results. The more conservative figures were used (ie, odds ratios computed from between-group differences). For the study by Herbst et al,²⁷ results from both the left and right sides were presented in the paper. The more conservative result (ie, left side) was chosen.

APPENDIX B

Hip Internal Rotation Strength



Abbreviations: IV, inverse variance; SE, standard error.

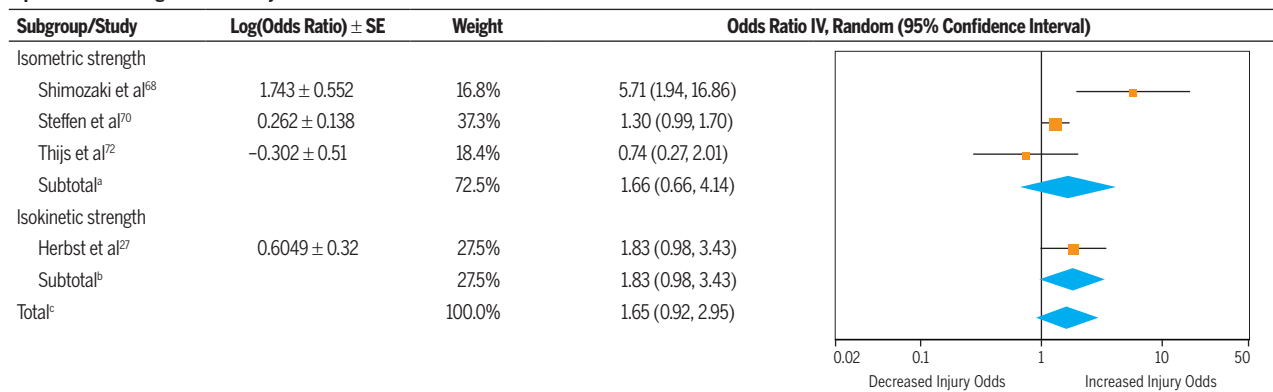
^aTest for overall effect: $z = 0.93$ ($P = .35$).

^bHeterogeneity: $r^2 = 0.10$, $\chi^2 = 1.57$, $df = 1$ ($P = .21$), $I^2 = 36\%$. Test for overall effect: $z = 0.59$ ($P = .56$).

^cHeterogeneity: $r^2 = 0.13$, $\chi^2 = 2.90$, $df = 2$ ($P = .24$), $I^2 = 31\%$. Test for overall effect: $z = 0.23$ ($P = .82$). Test for subgroup differences: $\chi^2 = 1.14$, $df = 1$ ($P = .29$), $I^2 = 12.3\%$.

FIGURE 3. Odds of knee injury with greater internal rotation strength.

Hip Abduction Strength: Female Only



Abbreviations: IV, inverse variance; SE, standard error.

^aHeterogeneity: $r^2 = 0.49$, $\chi^2 = 8.30$, $df = 2$ ($P = .02$), $I^2 = 76\%$. Test for overall effect: $z = 1.08$ ($P = .28$).

^bTest for overall effect: $z = 1.89$ ($P = .06$).

^cHeterogeneity: $r^2 = 0.22$, $\chi^2 = 9.04$, $df = 3$ ($P = .03$), $I^2 = 67\%$. Test for overall effect: $z = 1.69$ ($P = .09$). Test for subgroup differences: $\chi^2 = 0.03$, $df = 1$ ($P = .86$), $I^2 = 0\%$.

FIGURE 4. Odds of knee injury with greater hip abduction strength in female participants.

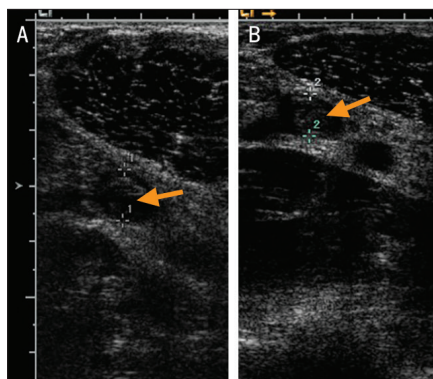


FIGURE 1. Short-axis-view, grayscale sonographic images of the right upper extremity, (A) without compression and (B) with compression, demonstrating an expanded noncompressible axillary vein (arrows) that contains echogenic material consistent with an occlusive thrombus.

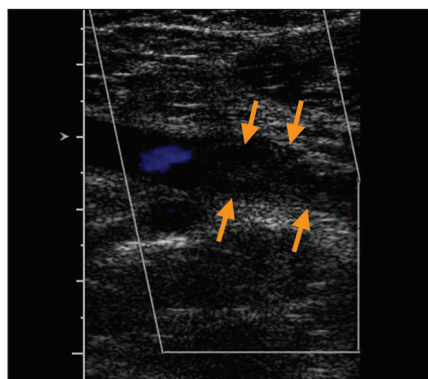


FIGURE 2. Long-axis color Doppler ultrasound image showing occlusion of the proximal right axillary vein (between the arrows).

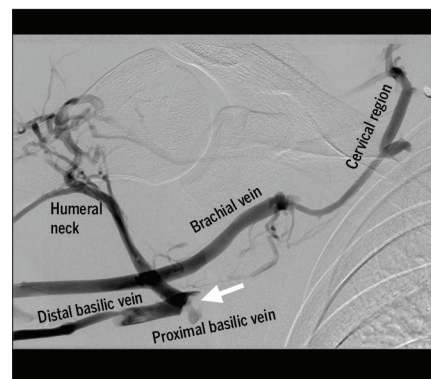


FIGURE 3. Right upper extremity digital subtraction venography. Contrast was injected via the distal basilic vein. There is occlusion of the proximal basilic vein (arrow), with reflux of contrast material into the brachial vein. Prominent venous collaterals are noted, extending toward the humeral neck and toward the cervical region. The axillary and subclavian veins are occluded by a thrombus and not visualized.

Upper Extremity Effort Thrombosis

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A 23-YEAR-OLD, RIGHT HAND-DOMINANT, male active-duty Marine self-referred to physical therapy with dull right anterior shoulder pain. The patient reported multiple episodes of transient and dull activity-related shoulder pain in the previous 6 weeks, despite no change in activity levels. He had been evaluated a month earlier for a similar complaint and diagnosed by his primary care physician with a shoulder strain. His symptoms resolved with taking time off from physical training, but returned following a typical physical training session on the day he presented to the physical therapy clinic.

The patient reported a dull, aching sensation in the anterior shoulder and transient arm swelling following exercise, but no radicular symptoms or tempera-

ture or pallor changes. No personal or family history of blood-clotting disorders was reported. Physical therapist examination demonstrated full cervical and upper extremity mobility and strength, without reproduction of symptoms. The Adson, Allen, and Halstead maneuver and the Roos test were negative. Following performance of 3 sets of 25 push-ups, asymmetrical venous distension was observed in the right upper arm and forearm.

The physical therapist referred the patient for a diagnostic ultrasound to rule out effort thrombosis of the axillary and subclavian veins.^{1,2} Same-day Doppler ultrasonography revealed an occlusive thrombus in the middle subclavian and axillary veins (FIGURES 1 and 2). The patient was admitted that day for intra-

venous anticoagulation therapy and catheter-directed thrombolysis (FIGURE 3).¹ Venography revealed incomplete resolution of the thrombus (FIGURE 4, available at www.jospt.org). The patient underwent balloon angioplasty, with hospital discharge on day 4. The patient continued oral anticoagulation therapy for 6 weeks and underwent prophylactic first-rib resection 2 weeks following angioplasty.

At 6 weeks post surgery, he was cleared for return to military duties. He then received physical therapy to restore shoulder function and was asymptomatic 6 months post surgery. Recurrence rates of less than 5% have been reported following multimodal treatment.² *J Orthop Sports Phys Ther* 2020;50(9):532. doi:10.2519/jospt.2020.9585

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- Hangge P, Rotellini-Coltvet L, Deipolyi AR, Albadawi H, Oklu R. Paget-Schroetter syndrome: treatment of venous thrombosis and outcomes. *Cardiovasc Diagn Ther*. 2017;7:S285-S290. <https://doi.org/10.21037/cdt.2017.08.15>

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or reflecting the views of the US Navy or Department of Defense.

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Sticking to It: A Scoping Review of Adherence to Exercise Therapy Interventions in Children and Adolescents With Musculoskeletal Conditions

The worldwide burden of musculoskeletal conditions (ie, diseases and injuries) is high and impacts people of all ages.^{28,33,82} In adolescence, the high prevalence of musculoskeletal pain (estimated to be between 20% and 40%)^{17,34,47} and incidence of musculoskeletal injuries (estimated at 30.9 injuries per 100 adolescents per year)²⁰ are concerning, given



their association with future musculoskeletal pain,^{31,35,74} obesity,⁹² osteoarthritis,⁹⁵ cardiovascular disease,⁴⁵ and all-cause mortality.^{1,98} Additionally, musculoskeletal pain in adolescence can reduce participation in school and sport⁴² and alter career choice later in life.⁷⁴ These long-term consequences underlie the importance of appropriate care for youth (ie, children and adolescents) with musculoskeletal conditions.

An essential treatment component for musculoskeletal conditions is exercise therapy. Distinct from general physical activity, “exercise therapy” is a regimen or plan of physical activities designed and prescribed in a precise dose to address specific therapeutic goals.⁶² In youth with musculoskeletal conditions, exercise therapy effectiveness is associated with adherence,^{10,49,76,78} defined as the extent to which someone’s behavior corresponds with agreed recommendations from a health care provider.¹⁰⁰ Despite the importance of adherence, consensus on how to define, measure, or improve adherence to exercise therapy is lacking.⁵

● **OBJECTIVE:** To identify and categorize barriers, facilitators, and strategies to boost exercise therapy adherence in youth with musculoskeletal conditions to inform research and clinical practice.

● **STUDY DESIGN:** Scoping review.

● **LITERATURE SEARCH:** We searched MEDLINE, CINAHL, SPORTDiscus, Scopus, PEDro, and ProQuest from inception to October 1, 2019.

● **STUDY SELECTION CRITERIA:** Studies written in English, with original data featuring an adherence barrier, facilitator, or boosting strategy for exercise therapy in youth (age, 19 years or younger) with musculoskeletal conditions, were included.

● **DATA SYNTHESIS:** Arksey and O’Malley’s framework and the PRISMA Extension for Scoping Reviews guided data synthesis. Study quality was assessed with the Mixed Methods Appraisal Tool. Descriptive consolidation included study and sample characteristics, exercise therapy details, and adherence measurement specifics. Inductive thematic analysis of adherence barriers, facilitators, and boosting strategies followed Braun and Clarke’s 6-step guide.

● **RESULTS:** Of 5705 potentially relevant records, 41 studies, representing 2020 participants (64% girls; age range, 2–19 years) with 12 different musculoskeletal conditions and multiple exercise therapy interventions, were included. Despite poor reporting of adherence concepts, time constraints, physical environment (eg, location), and negative exercise experiences were commonly identified barriers. Social support and positive exercise experiences were frequently identified facilitators. Reinforcement, exercise program modification, and education were recurring boosting strategies, despite being infrequent barriers or facilitators.

● **CONCLUSION:** A diversity of barriers to and facilitators of exercise therapy for youth with musculoskeletal conditions were identified. Efforts to link adherence-boosting strategies to an individual’s needs should be considered. Making exercise enjoyable, social, and convenient may be important to maximizing adherence in this population. *J Orthop Sports Phys Ther* 2020;50(9):503–515. Epub 1 Aug 2020. doi:10.2519/jospt.2020.9715

● **KEY WORDS:** behavior change, compliance, injury, participation, rehabilitation, youth

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Identifying predictors of exercise therapy adherence/nonadherence (ie, barriers and facilitators) is a key first step to developing strategies aimed at improving adherence.⁶⁷ A variety of barriers,^{40,68,86} facilitators,²³ and adherence-boosting strategies^{41,57,58} have been identified in adults with musculoskeletal conditions. However, these concepts are context specific⁵⁶ and likely differ for youth, given their unique physiological (eg, skeletal immaturity),⁹⁰ cognitive (eg, brain development),¹³ and social (eg, schooling, peer influences)⁷² characteristics. For example, schoolwork is a unique and important consideration for youth exercise therapy, and its impact on adherence likely varies by setting (eg, in class versus homework), grade level, and month. The paucity of studies investigating these concepts in youth is a substantial hurdle to improving exercise therapy adherence, enhancing clinical outcomes, and decreasing the long-term consequences of youth musculoskeletal conditions.

The aim of this scoping review was to consolidate existing knowledge and identify knowledge gaps to direct future research aimed at improving the effectiveness of exercise therapy interventions in youth with musculoskeletal conditions. The primary objective was to identify and categorize key themes in the existing evidence base pertaining to exercise therapy adherence barriers, facilitators, and boosting strategies in youth with musculoskeletal conditions. The secondary objective included identifying knowledge gaps and providing recommendations for future inquiry and clinical practice.

METHODS

Framework, Protocol, and Registration

DUE TO THE BROAD RESEARCH QUESTION and diverse evidence base, a scoping review methodology was selected. The 5-step methodological framework proposed by Arksey and O'Malley³ was followed, with consideration of subsequent recommendations by Levac et al⁵³ and the Joanna Briggs Institute.⁴

The study team had combined expertise in quantitative methodology, behavior change theory, clinical prescription of exercise therapy, and pediatric rehabilitation. This scoping review is reported according to the PRISMA Extension for Scoping Reviews.⁹³ At the initiation of this review, there was no database for registering a priori scoping review strategies.

Search

Relevant studies were identified in a search of 6 online databases (ie, MEDLINE, CINAHL, SPORTDiscus, Scopus, PEDro, and ProQuest), from inception to October 1, 2019, based on their relevance to the topic. The search strategy (ie, Medical Subject Headings, key words) was developed in consultation with a library scientist and content experts (see **APPENDIX A**, available at www.jospt.org). Reference lists of included studies, relevant reviews, and clinical guidelines were examined to identify additional relevant records. Search results were organized using the reference management software EndNote X8.2 (Clarivate Analytics, Philadelphia, PA).

Study Selection

After accounting for duplicate studies, titles and abstracts were independently screened for exclusion by 2 raters blinded to author(s) and journal title, using a Microsoft Excel (Microsoft Corporation, Redmond, WA) workbook.⁹⁴ Prior to title/abstract screening, all reviewers independently screened a random sample of 120 titles/abstracts to assess the applicability of the exclusion criteria. All raters achieved acceptable interrater agreement (84%-97%, $\kappa = 0.45-0.84$) with the senior author. Common discrepancies within the rater group were reviewed/clarified before screening commenced. Finally, 2 independent raters reviewed the full text to identify studies to be included. Consensus was reached on disagreements, first between raters and then, if required, with the senior author.

Studies were included if they reported or investigated a barrier, facilitator, or

strategy to boost adherence (or compliance) to an exercise therapy intervention in children or adolescents (age, 19 years or younger) with a musculoskeletal condition (injury or disease). For this review, an adherence-boosting strategy was defined as an a priori specific action that was discussed and implemented by the investigators, with the intent of improving adherence. Additional inclusion criteria included English-language and peer-reviewed research with original data (ie, peer-reviewed publications and theses). Due to the broad nature of the construct "musculoskeletal condition," the initial search was not limited by condition to ensure that no relevant records were missed. Instead, records were excluded at the title/abstract screening stage if they did not include youth with a musculoskeletal condition. Similarly, inclusion based on the construct "adherence" was applied at the full-text review stage to ensure that no sources of evidence were excluded when adherence concepts were not featured in the title or abstract. Corresponding authors were contacted via e-mail for clarification if needed.

Quality Assessment

As recommended by Levac et al⁵³ and Daudt et al,¹⁶ the methodological quality of included studies was assessed prior to data charting. Each study was independently rated by 2 authors using a customized version of the 2018 Mixed Methods Appraisal Tool (MMAT) (**APPENDIX B**, available at www.jospt.org). The decision to use the MMAT was based on its ability to assess internal and external validity across multiple study designs, and on its measurement properties (ie, efficiency, reliability, and content validity).^{36,71,87} The MMAT scores did not inform the interpretation of identified themes, but were used to provide context and transparency about the methodological strengths and weaknesses of the studies on which themes were based. The MMAT category scores were also used to identify consistent methodological weaknesses in the existing evidence base and form recom-

mentations on how future studies could be improved.

Data Charting

Data charted from each study included study year, location, and study design; participant age, sex, and musculoskeletal condition; exercise therapy type, setting, supervision level, and quantity; adherence rate, outcomes, and instruments; and barriers, facilitators, and adherence-boosting strategies. An a priori decision was made not to extract the effect of adherence-boosting strategies, due to the heterogeneity of study designs. Data charting was completed by the lead author using a custom-designed form developed and piloted by the study team (APPENDIX C, available at www.jospt.org). Prior to data charting, the performance of the form was assessed by comparing data extracted independently by the lead and senior authors from studies of quantitative and qualitative designs. This resulted in small revisions to ensure all relevant data were captured across study designs. Duplicate data charting for all records was not completed due to lack of feasibility.

Data Synthesis

Study details, sample characteristics, intervention details, and adherence concepts were described and numerically summarized. A review studying adherence to exercise therapy in adults⁵ was used as a template to present intervention and adherence measurement details, allowing for comparison of adherence measurement between youth and adults. Individual adherence barriers, facilitators, and boosting strategies were identified and grouped into prevalent topics. Braun and Clarke's 6-stage guide to thematic analysis⁹ was applied to inductively identify topics and recurrent themes. Themes were organized into behavior change elements using the capability, opportunity, motivation-behavior (COM-B) framework⁶⁰ to help identify knowledge gaps. Theme identification and COM-B categorization were developed and trialed by the lead and senior authors until consensus was reached. Regular

study team meetings were held to discuss and agree on emerging themes and interpretations. A flow chart of methodological frameworks employed in this review is provided in FIGURE 1.

RESULTS

Study Selection

OF 9272 POTENTIAL RECORDS, 5705 unique records underwent title/abstract screening, 303 were reviewed in full, and 41 studies were included (FIGURE 2). We attempted to contact one author on 2 occasions over 30 days to clarify sample characteristics to determine one study's eligibility for inclusion.³⁸ The author did not respond, so the record was excluded.

Quality Appraisal

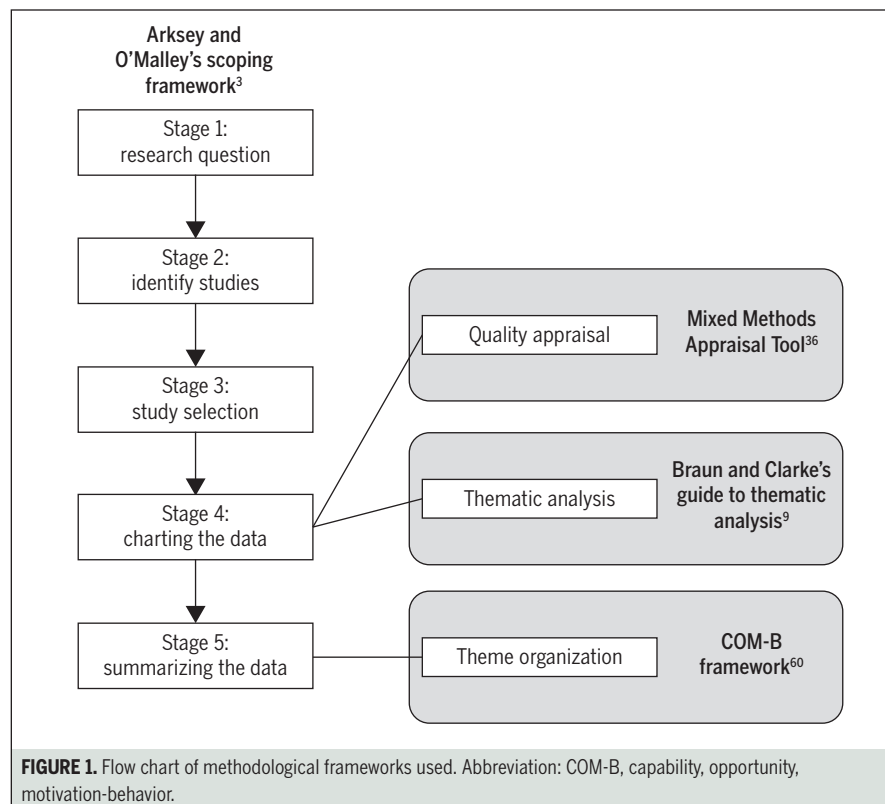
The MMAT ratings of included studies are summarized in APPENDIX C. Fourteen studies (34%) were rated as high quality (scoring 4-5), 12 studies (29%) were of moderate quality (scoring 3), and 15 stud-

ies (37%) were of poor quality (scoring 1-2). Overall, studies rated poorly on internal validity, including "administration of the assigned intervention" (quantitative studies) and "substantiation of results from the data" (qualitative studies).

Study Characteristics

APPENDIX C summarizes the characteristics of the included studies. Sixteen of the 41 included studies were randomized controlled trials, 13 were nonrandomized quantitative studies (eg, pre-experimental, cohort, cross-sectional), 4 were quantitative descriptive studies (eg, case series, case report), and 8 were qualitative studies.

Studies represented data from 2020 participants (1292 girls), ranging in age from 2 to 19 years, from 14 countries. Across studies, 12 musculoskeletal conditions were represented, including adolescent idiopathic scoliosis (29% of studies), juvenile idiopathic arthritis (29%), patellofemoral pain (12%), and fibromyalgia (5%) (see APPENDIX C). Twenty-nine stud-



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ies (71%) involved conditions that typically require long-term management (eg, juvenile idiopathic arthritis, idiopathic scoliosis), and the remaining 12 studies (29%) concerned conditions typically associated with shorter-term treatment (eg, low back pain, patellofemoral pain).

TABLE 1 summarizes exercise therapy details, which were fully reported in only 56% of studies (n = 23). Exercise program length ranged between 3 and 160 weeks, with individual sessions lasting 15 to 120 minutes, at a frequency of 1 to 21 sessions per week. Some programs, especially those for conditions requiring long-term management (eg, juvenile idiopathic arthritis, idiopathic scoliosis), were exceptionally long (ie, multiple years) or frequent (ie, multiple sessions per day).

Forty-nine percent of exercise therapy programs were multimodal (eg, strength and aerobic components), 49% involved partial supervision (ie, a mix of supervised and unsupervised exercise), and 49% were completed in combined settings (eg, home and clinic components).

Adherence variables are summarized in **TABLE 2**. Only 37% (n = 15) of included studies reported a minimal acceptable adherence goal, which ranged between 31% and 100% of prescribed exercises. Similarly, only 54% (n = 22) reported adherence, which ranged between 12% and 99% of prescribed exercises. The most commonly used adherence outcome and instrument were “session completion” (39% of studies) and “self-reported exercise log” (54% of studies), respectively. Several technolo-

gies were identified to help measure adherence, such as accelerometers^{73,77} and games/electronic applications.^{96,102} Operational (eg, calibration, time required) and feasibility (eg, equipment, cost) concerns were commonly discussed; 1 study discouraged the use of electronic applications for exercise tracking.¹⁰²

Thematic Synthesis

Of the 222 data items related to exercise therapy adherence, 62 unique topics and 11 themes were identified. Twelve percent of data items were related to capability (3 themes), 48% to opportunity (4 themes), and 41% to motivation (4 themes). **TABLE 3** summarizes the frequency of identified themes and the quality of supporting studies, organized by adherence modifier (barriers, facilitators, and strategies to improve adherence) and COM-B category.

Barriers to Exercise Therapy Adherence

Twenty-two studies including 856 participants identified barriers to exercise therapy adherence. The majority related to the opportunity to exercise, with “time”^{8,18,29,39,44,55,81,83-85,99} and “physical environment”^{8,22,29,39,44,55,88,89,91,99} being the most commonly reported. With respect to motivation, personal experience during exercise was the most commonly identified barrier, with pain,^{18,27,48,83,85} boredom,^{8,18,22,96} and an overall lack of enjoyment^{2,83,88} identified. Barriers related to capability included psychological traits (eg, lack of confidence, forgetfulness),^{18,39,78,83} physical traits (eg, fatigue),^{29,83} and not understanding the purpose of the exercises.^{2,18}

Facilitators of Exercise Therapy Adherence

Twenty-five studies including 962 participants identified a facilitator of exercise adherence. Most facilitators involved the opportunity to adhere, with the social environment being the most commonly identified. Group exercise programs,^{18,44,83} involving family with the exercise program,^{2,8,39,83,101,102} and peer support (whether in person⁴⁴ or online⁹⁹) were helpful,

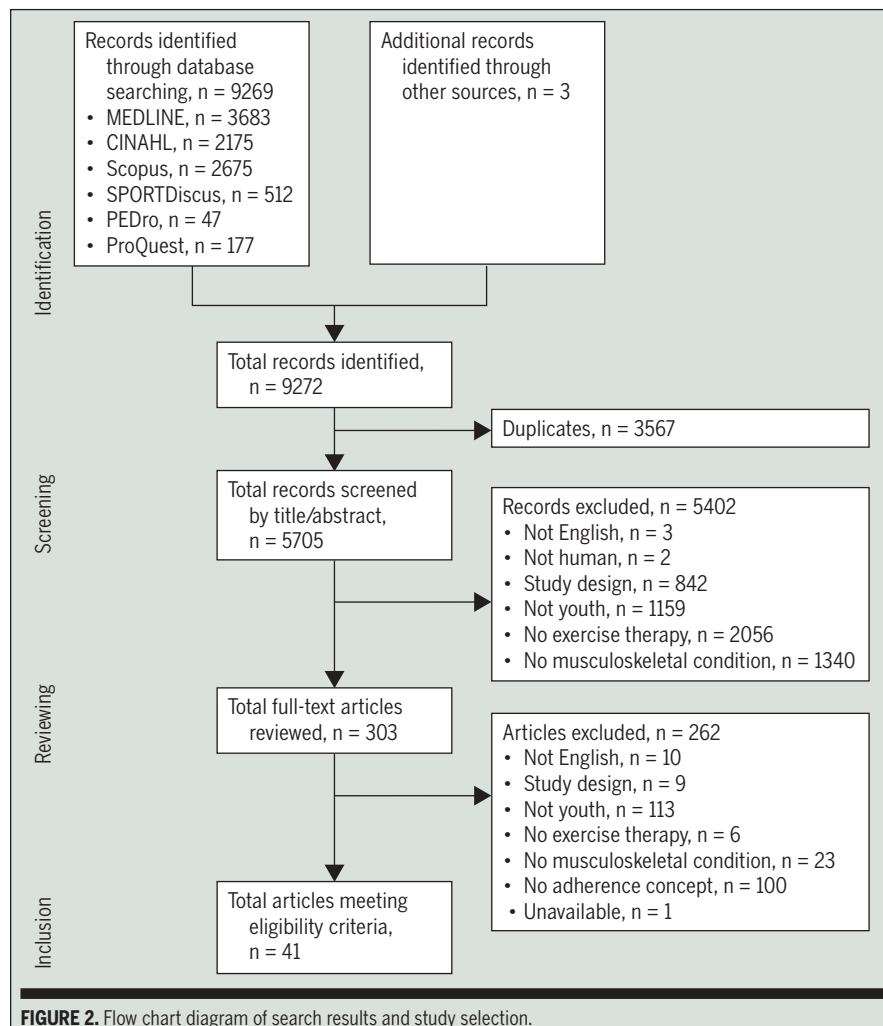


FIGURE 2. Flow chart diagram of search results and study selection.

as was a strong therapeutic alliance between the participant and prescribing clinician.^{19,44,85} Facilitators related to motivation included exercises that relieved pain and/or other symptoms,^{8,22,26,102} were fun,^{8,18,22,26,59,83,84,96,102} or were modified to include other enjoyable activities.¹⁸

Conflicting Evidence

Some topics were identified as both barriers to and facilitators of adherence. Location for exercise (physical environment) was the most inconsistent, with exercising at home,^{29,75} at a pool,²² and in the community³⁹ all described as preferred locations for exercise, while home²⁹ and pool²² locations were also identified as barriers. Goal setting was a facilitator in 3 studies,^{39,99,102} but was also identified as a barrier when goals were not patient led or not regularly achieved.²⁴ While exercise handouts were generally facilitating, both written material⁴⁴ and video material⁹⁹ were preferred over each other in different studies. The group environment was mostly facilitating, but was identified as a barrier in 1 study, making some participants feel “uncomfortable.”⁸³ While patient choice in exercise planning was facilitating,^{19,32,75,99} tension was highlighted between allowing patient involvement in program design and still achieving the minimum exercise dose required to achieve clinical effect.⁸³

Adherence-Boosting Strategies

Thirty studies including 1547 participants identified an adherence-boosting strategy, of which improving motivation through reinforcement was the most commonly identified (17 studies). This included clinicians “checking in,”^{21,39,59,63,75,85,88,89,102} clinicians or parents monitoring/reviewing exercise diaries,^{44,48,49,61,78,91,99} and rewards^{48,85,88} (eg, stickers, gifts, computer time). Exercise program modifications, including regular exercise progressions or variations,^{48,61,84,91} teaching exercise technique,^{39,48,91} and provision of written^{12,29,44,78} or video^{84,88,103} instructions for reference at home, were frequently used. No identified strategies

specifically targeted physical or psychological characteristics, though targeting participants’ beliefs was common, including educational programs about their condition,⁶¹ the purpose of exercise,^{19,26,44,48,61,91,97} and the consequences of nonadherence.^{50,73,77,78}

Comparisons Across Diagnosis, Age, and Sex

Most studies did not differentiate barriers/facilitators by diagnosis, sex, or age. When comparisons were possible, common themes of exercise experience, time, and physical environment were generally identified across groups. However, some differences existed. The social environment and exercise experience as adherence-boosting strategies were identified more frequently for conditions requiring long-term management.^{32,44,48,103} While few studies reported findings specifically for boys, 5 of the 8 studies including only girls highlighted the importance of the social environment, including peer support^{39,99} or group exercise.^{32,44}

With respect to age, most studies included participants spanning diverse age groups and did not differentiate findings by age. These included the 3 studies with children younger than 8 years of age.^{22,27,91} The studies including only school-aged children (age, 8-14 years) identified the importance of a positive exercise experience^{26,85,88,96} and a strong therapeutic alliance between patient and clinician.^{19,85} For early adolescents (age, 10-14 years), time constraints (especially homework) were frequent barriers,^{81,88} and involving family to boost adherence was a common strategy.^{61,80} The 6 studies focusing on older adolescents (age, 15-19 years)^{24,50,64,73,76,77} repeatedly highlighted education,^{50,73,77} feedback,^{73,77} and the use of technology-enabled reminders (short message service messages) as adherence modifiers.^{64,73}

Alignment Between Barriers/Facilitators and Boosting Strategies

FIGURE 3 links identified barrier/facilitator themes to boosting-strategy themes

TABLE 1		EXERCISE THERAPY INTERVENTION CHARACTERISTICS	
			Value
Type of exercise, n (%)			
Multimodal			20 (49)
Strength training			9 (22)
Aerobic training			4 (10)
Motor control			3 (7)
Not reported			5 (12)
Supervision, n (%)			
Partial			20 (49)
None			9 (22)
Full			8 (20)
Not reported			4 (10)
Setting, n (%)			
Combined			20 (49)
Home			13 (32)
Clinic/hospital/school			3 (7)
Not reported			5 (12)
Quantity			
Prescribed session length, min			15-120
Prescribed session frequency, sessions/wk			1-21
Prescribed program length, wk			3-160

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TABLE 2

REPORTED ADHERENCE RATES, OUTCOMES, AND INSTRUMENTS

	Value
Adherence goal, % of prescribed ^a	31-100
Adherence rate, % of prescribed ^b	12-99
Adherence outcome, n (%) ^c	
Session completion	16 (39)
Exercise frequency	9 (22)
Exercise intensity	3 (7)
Exercise time	3 (7)
Session attendance	2 (5)
Exercise replication	1 (2)
Behavior component	1 (2)
Not reported	8 (20)
Adherence measurement tool, n (%) ^c	
Self-reported exercise log	22 (54)
Class register	12 (29)
Technological tool	6 (15)
Interview	5 (12)
Existing measurement scale	2 (5)
E-mail survey	1 (2)
Health care provider observation	1 (2)
Not reported	8 (20)

^aNot reported, n = 26 (63%).
^bNot reported, n = 19 (46%).
^cPercentages may total more than 100%, given that some studies reported multiple adherence outcomes/measures.

to illustrate the degree to which they align. Strategies that focused on reinforcement, beliefs, and program details were commonly employed, despite few studies identifying them as barriers or facilitators. Several identified barriers and facilitators (ie, physical characteristics, psychological characteristics, and goal setting) have yet to be targeted by a boosting strategy. While these comparisons simply indicate where the bulk of the evidence lies, they also point to opportunities (ie, barriers/facilitators that have not yet been targeted with boosting strategies) and bring into question how boosting strategies are chosen (ie, feasibility versus alignment with known barriers/facilitators in a specific population or individual).

DISCUSSION

THE MOST COMMON BARRIERS TO Exercise therapy for youth with musculoskeletal conditions included time constraints, physical environment, and negative exercise experiences. Social environment and positive exercise experiences were the most commonly highlighted facilitators. Reinforcement, program modification, and education were the most common adherence-boosting strategies, despite not aligning with identified barriers or facilitators. Overall, there has been greater focus on how opportunity and motivation influence adherence versus one's capability, and strategies that target exercise experience, time, goal setting, and individual physical or psychological characteristics have largely been unexplored. Our findings also highlight considerable heterogeneity in methods for measuring and operationalizing adherence, and inconsistency in how adherence concepts are reported.

Comparisons to Adults With Musculoskeletal Conditions

There were similarities between our findings and what is known about exercise therapy adherence in adults with

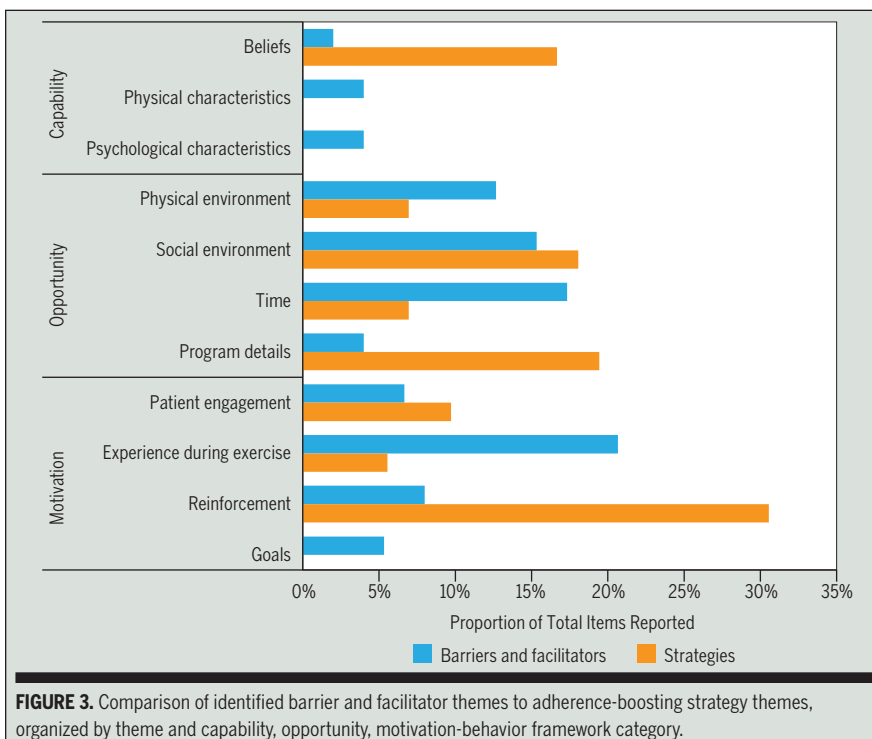


FIGURE 3. Comparison of identified barrier and facilitator themes to adherence-boosting strategy themes, organized by theme and capability, opportunity, motivation-behavior framework category.

musculoskeletal conditions. Experiences during exercise (ie, boredom, pain), program length (ie, number of exercises, time required), and lack of social support appear to be barriers to exercise therapy adherence in youth and adults with musculoskeletal conditions.^{23,40,68} In contrast, baseline physical activity,^{23,40} previous nonadherence,^{23,40} and psychological characteristics such as depression,⁴⁰ stress,^{23,40} and anxiety⁴⁰ are barriers to exercise therapy in adults, but not in youth. Self-efficacy (defined as the “belief about one’s capabilities to produce designated levels of performance”⁶), which is commonly associated with exercise therapy adherence in adults,^{23,25,40,43,69,70} had minimal representation in the studies included in our review. This was surprising, given that self-efficacy is a strong predictor of adherence to treatments for children with diabetes⁶⁶ and asthma.¹⁴ Barriers unique to youth that have not been identified in adult studies include transportation and school responsibilities. Although these differences may point to concepts that are unique to youth or adult populations, they may also simply represent unexplored areas that are in need of further investigation.

Comparisons to Youth With Other Medical Conditions

Similarities exist between exercise therapy adherence in youth with musculoskeletal conditions and youth with other medical conditions. Family involvement, time constraints, and the exercise experience are associated with prescribed exercise adherence in youth with obesity (age, 13-17 years)⁴⁶ and cystic fibrosis (age, 10-16 years).³⁰ Factors influencing exercise therapy adherence in youth may be more related to age and social context than to health condition.

One inconsistency observed involved the social environment. While we found that the social environment facilitated adherence in all but 1 study,⁸³ a scoping review of youth living with obesity repeatedly found that adherence to exercise was negatively impacted if friends

were inactive (eg, role modeling), or if the person had experienced activity-related teasing (eg, bullying by peers).⁴⁶ One possible explanation for this divergence is that physical appearance and body image (a common source of social stigma) could play a larger role in youth living with obesity than with musculoskeletal conditions.

Boosting Strategies

The most commonly employed adherence-boosting strategies identified in our review are consistent with behavior change techniques. These include reinforcement (eg, feedback and monitoring),⁷⁹ program modification (eg, exercise practice/rehearsal),⁵⁸ education (eg, instruction/demonstration of behavior),^{7,58} and so-

TABLE 3

IDENTIFIED THEMES ORGANIZED BY COM-B CATEGORY AND TOPIC

Theme Frequency (Study Quality)/Topic ^a			
COM-B Category/ Theme	Barrier	Facilitator	Strategy
Capability			
Beliefs	2 (1-5) • Understanding the purpose of exercise (lack of) ^{2,18}	1 (2) • Perceived helpfulness of treatment ²⁷	12 (1-4) • Education on the purpose of exercise ^{19,26,44,48,61,91,97} • Consequences of noncompliance ^{73,77,78} • Education about condition ⁴¹
Physical characteristics	4 (2) • Fatigue ²⁹ • Other symptoms ^{29,83}	2 (1-2) • Age ^{2,27}	0
Psychological characteristics	4 (3-5) • Personality traits ⁷⁸ • Confidence (lack of) ³⁹ • “Laziness” ¹⁸ • Forgetfulness ⁸³	2 (3) • Personality traits ⁷⁸ • Self-confidence ⁴⁴	0
Opportunity			
Physical environment	13 (1-4) • Transportation ^{22,39,44,85,88,89,91} • Privacy (lack of) ^{8,22,99} • Location (pool) ²² • Location (home) ²⁹	6 (2-4) • Location (home) ^{29,75} • Location (community) ³⁹ • Location (pool) ²² • Cost ⁷⁵ • Equipment ⁴⁴	5 (2-5) • Provided equipment ^{29,80} • Cost ⁴⁴ • Location (school) ⁷⁶ • Provide access to facility ⁸⁰
Social environment	1 (3) • Group environment ⁸³	22 (1-5) • Family involvement ^{2,8,39,83,101,102} • Group environment ^{18,44,83} • Therapeutic alliance ^{18,19,44,85} • Comparison to others ^{39,44} • Peer support (in person) ⁴⁴ • Peer support (social media) ⁹⁹ • Social participation ¹⁰²	13 (1-5) • Family involvement ^{19,59,61,75,76,80} • Online chat forum ⁹⁹ • Involve friends ⁴⁸ • Therapeutic alliance ⁸⁸ • Trained caregiver ⁶³ • Offer of support ^{101,102} • Group exercise to promote compliance ³²
Time	17 (2-5) • Time constraints ^{8,18,29,83-85} • School responsibilities ^{39,44,55,81,99} • Exercise schedule ⁹⁹ • Exercises take too long ⁸³	9 (1-5) • Exercise schedule ^{8,18,39,44,84,99} • Exercise quantity ^{24,103} • Time (available) ⁷⁵ • Recreational activities ⁵⁵	5 (1-4) • Exercise quantity ^{49,91} • Flexible exercise schedule ^{5,89} • Sessions outside school hours ⁴⁴

Table continues on page 510.

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cial support.⁵⁸ However, despite goal setting being an effective strategy in adults with low back pain,¹⁵ osteoarthritis,⁶⁵ and chronic musculoskeletal pain⁵⁸ and in youth with obesity⁴⁶ and cystic fibrosis,³⁰ there is a paucity of evidence of its value as an adherence-boosting strategy in youth with musculoskeletal conditions. Similarly, while targeting the exercise experience to help encourage adherence is an effective strategy for adolescent physical activity¹¹ and youth with cerebral palsy,^{37,51}

it is relatively unexplored as an adherence-boosting strategy in youth with musculoskeletal conditions. Targeting both goal setting and exercise experience may be important strategies for improving adherence in this population.

Caregiver Involvement and Autonomy

Another important consideration related to adherence for youth is the impact of caregiver involvement. Multiple studies identified that involving caregiv-

ers with exercise can facilitate adherence,^{2,8,39,83,101,102} and can improve exercise completion²⁷ and adherence reporting,² especially for younger patients. For this reason, it is common in clinical practice for communication to focus on the caregiver rather than on the child. Unfortunately, patient autonomy and the therapeutic alliance between the patient and clinician may be sacrificed with this approach, potentially impacting adherence. Many of the identified themes in our review support involving the individual patient (rather than the caregiver) in treatment planning to help foster autonomy and engagement. For example, individualization,^{29,44,91} patient preference,^{19,32,75,99} accountability,^{8,27} and goal setting^{39,99,102} were identified in studies on youth of all ages, reinforcing the importance of involving the patient (regardless of age) in exercise uptake. This tension between increasing caregiver involvement and fostering patient autonomy is an important consideration when prescribing exercise to youth and likely requires balance.

Diagnosis, Sex, and Age Considerations

It is not surprising that differences between condition groups exist, given that motivations for managing a long-term or lifelong condition likely differ from those for managing an acute injury with defined healing times. One example of how this difference could impact adherence involved the social environment, specifically how group exercise was mostly only utilized for long-term conditions.^{18,32,44,83} Group programs may simply be offered more often in hospital settings (where many long-term conditions are followed) than in private outpatient clinics (where acute injuries are often treated). However, this difference could also indicate that social support plays a larger role in maintaining motivation throughout the lengthy treatment process required for some conditions. Regardless, targeting the social environment through group exercise and its impact on exercise adherence is a relatively unexplored area for acute musculoskeletal injuries.

TABLE 3

IDENTIFIED THEMES ORGANIZED BY COM-B CATEGORY AND TOPIC (CONTINUED)

Theme Frequency (Study Quality)/Topic ^a			
COM-B Category/ Theme	Barrier	Facilitator	Strategy
Program details	3 (2-4) - Exercise complexity⁹¹ - Exercise handouts (written only)⁹¹ - Exercise progression (lack of)⁹⁶	3 (3-4) - Exercise handouts (video)⁹⁹ - Exercise handouts (written)⁴⁴ - Exercise intensity⁸⁵	14 (1-4) - Exercise progression^{48,61,84,91} - Exercise teaching^{39,48,91} - Exercise handouts (video)^{84,88,103} - Exercise handouts (written)^{12,29,44,78}
Motivation			
Patient engagement	1 (4) Accountability (lack of)⁸	9 (2-4) - Patient choice^{39,32,75,99} - Accountability²⁷ - Diary keeping²⁴ - Exercise contract⁹⁹ - Individualization^{44,91}	7 (1-4) - Individualization^{29,44,48,63,91} - Exercise contract⁹⁹ - Patient choice⁷⁶
Experience during exercise	14 (1-5) - Pain during exercise^{18,27,48,83,85} - Boredom during exercise^{8,18,22,96} - Symptom relief (lack of)^{22,24} - Enjoyment of exercise (lack of)^{2,83,88}	18 (2-5) - Enjoyment of exercise^{8,18,22,26,59,83,84,96,102} - Symptom relief^{8,26,102} - Competition^{8,39,96} - Pain during exercise (lack of)²²	4 (1-4) - Enjoyment of exercise^{39,103} - Keep exercise pain free⁴⁴ - Music during exercise⁴⁸
Reinforcement	2 (1-4) - Feedback on exercises (lack of)⁷³ - Supervision (lack of)⁸	10 (2-5) - Clinician checking in^{39,99,103} - Rewards^{8,18,85} - Feedback^{77,96} - Technology as reminder^{64,102}	22 (1-5) - Clinician checking in^{21,39,59,63,75,85,88,89,102} - Review of diaries^{44,48,49,61,78,91,99} - Rewards^{48,85,88} - Reminders^{75,76}
Goals	5 (1-5) - Goal setting²⁴ - Prioritization^{18,55,83}	3 (2-4) Goal setting^{39,99,102}	0

Abbreviation: COM-B, capability, opportunity, motivation-behavior.

^aThe number of times themes were identified (most frequent are in bold), study quality ratings (range, 0-5, where higher scores indicate higher quality), and unique topics identified within themes.

It is also understandable that youth of diverse sexes and ages may be affected by social support differently. Social support is known to influence physical activity in girls⁵²; this finding was echoed in our study, where the social environment was repeatedly identified as a facilitator for girls but not for boys.^{19,39,44,99} This could indicate an important sex difference consideration when planning exercise prescription. Similarly, while the social environment was facilitating across age groups, there were subtle differences in the type of support desired. While peer/group support was identified across ages, a strong therapeutic alliance was facilitating in children aged 8 to 11 years,^{19,85} and family support was highlighted in early adolescence (age, 10-14 years).^{61,80}

Clinical Implications

There are several implications for clinicians hoping to help youth “stick to” their prescribed exercises that arise from this review. Open discussion with patients (regardless of age) and their caregivers at the time of exercise prescription provides an opportunity to discuss the importance of exercise adherence, agree on achievable adherence levels, and devise a strategy to evaluate exercise completion. Given the heterogeneity of barriers, facilitators, and adherence-boosting strategies, it may be important for clinicians to take time to identify the barriers and facilitators unique to each patient, then choose a boosting strategy that either targets barriers or promotes facilitators. **TABLE 4** provides practical examples of how adherence-boosting strategies can be applied to address common barriers and facilitators.

Knowledge Gaps and Future Research

Future qualitative studies should report how data were derived from interviews. Future quantitative investigations should report outcome measurement properties (eg, validity and reliability), exercise intervention details (ie, sufficient detail to be reproduced), and effect of adherence-boosting strategies. Overall, a standard-

ized approach for measuring adherence concepts is needed, and reporting the percentage of prescribed exercises completed (regardless of measurement tool) would enable pooling of results. Given the possible influences of age and sex identified in this review, future studies should consider age and sex when targeting or reporting adherence. Last, calls for consistent use of the term *adherence* rather than *compliance* to describe exercise completion should be respected.^{54,56}

Studies focusing on the relationship between adherence, exercise effectiveness, and health outcomes in youth with musculoskeletal conditions are needed. These studies should consider stakeholder consultation throughout the

process to ensure that future research is pertinent, feasible, and applicable to those user groups. Potential stakeholders (and topics) include patients (eg, preferred strategies, terminology, applicability of recommendations), caregivers (eg, caregiver involvement, feasibility of exercise programs), and clinicians (eg, clinical considerations, behavior change coaching). Improved consistency of adherence measurement and reporting is required prior to the development of new tools and interventions. However, future research directions could include linking strategies to barriers/facilitators, evaluating their effectiveness, and developing screening tools to identify barriers/facilitators at an individual level. Future

TABLE 4

EXAMPLES OF LINKING ADHERENCE-BOOSTING STRATEGIES TO COMMON BARRIERS AND FACILITATORS

Theme/Barrier or Facilitator	Practical Example of Adherence-Boosting Strategy
Time	
Fewer exercises (facilitator)	Consider limiting number of exercises to minimize time commitment ^{49,85,91,103}
Experience during exercise	
Exercise enjoyment (facilitator)	Children: consider using games and crafts during exercise ¹⁸ ; incorporate preferred and recognizable activities into exercises (eg, favorite sport) ¹⁰³ Adolescents: suggest that adolescents select their own motivating music or TV during exercise ^{39,83} ; consider making exercises into games or competition ^{8,39,96} ; incorporate technology/social media into the exercise routine ⁹⁹
Painful exercises (barrier)	Check in often to ensure that exercises are comfortable ²²
Boring exercises (barrier)	Progress or change exercises regularly to prevent monotony ⁹⁶ When possible, consider distraction techniques during exercise, including books, games, and technology ⁹⁶
Social environment	
Involving family (facilitator)	Invite parents and/or siblings to participate in exercises (eg, family challenge) ⁸
Involving friends (facilitator)	Invite friends to participate in exercises (eg, bring a friend to “physio day”) ⁴⁸
Strong therapeutic alliance (facilitator)	Establish good therapeutic alliance early through interaction and collaboration ⁹ For group exercise classes, consider reducing the therapist-participant ratio for more one-on-one attention ^{85,88}
Group exercises (facilitator)	Consider group exercise classes for similar conditions/ages ^{18,32,44,83} Involve school teachers to possibly incorporate exercise into classroom routines ¹⁸
Online support groups (facilitator)	Seek condition-specific online forums or chat rooms for youth ⁹⁹
Physical environment	
Transportation issues (barrier)	Design programs that are not dependent on location for completion ⁷⁶ Consider unconventional locations for exercise routine (eg, school, park, pool) ^{18,22,76} For supervised exercise, offer multiple locations for sessions and consider factors such as proximity to home and parking ^{76,85,91}
Minimal equipment needs (facilitator)	When possible, provide equipment or design programs with minimal equipment requirements ^{29,80}

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studies should consider targeting self-efficacy, goal setting, the experience during exercise, and the social environment, based on their association with behavior change in other populations.

Limitations

It is possible that not all relevant studies were identified, despite a systematic search strategy and duplicate screening. It is also possible that sources excluded due to study design (eg, editorials, blogs) might have contributed additional information related to these topics. Not all barriers and facilitators to adherence may have been identified, given the overall poor reporting of adherence concepts. To minimize possible theme misclassification due to category overlap, we used piloted charting tools and regular team meetings to discuss and iteratively adjust theme interpretation.

While study quality was reported to help identify knowledge gaps, study quality ratings may not be related to the adherence concepts reported but, rather, to the efficacy and reporting of the exercise program. Additionally, studies were not excluded based on quality rating, possibly impacting the validity of reported findings. Despite including a wide variety of conditions, ages, and interventions, the generalizability of our findings may be limited, as not all musculoskeletal conditions were reflected. Formal stakeholder consultation did not take place as part of this review, though the study team comprised multiple clinicians who were able to add that perspective to the interpretation. We have emphasized the frequency of reported themes. However, frequency does not necessarily reflect the importance of certain themes to adherence, simply how often they have been investigated or identified.

CONCLUSION

TIME CONSTRAINTS, LOCATION, social support, and the experience during exercise were important considerations for exercise therapy ad-

herence in youth with musculoskeletal conditions. Reinforcement, program modification, and education were popular adherence-boosting strategies. Clinicians and researchers should consider choosing adherence-boosting strategies that align with the individual patient's needs and preferences. ●

KEY POINTS

FINDINGS: Many popular adherence-boosting strategies for youth with musculoskeletal conditions, including reinforcement and education, do not align with common barriers (program length, inconvenient location, and negative exercise experiences) and facilitators (social support and positive exercise experiences) for exercise therapy.

IMPLICATIONS: Clinicians and researchers should consider adherence-boosting strategies that align with an individual's barriers and facilitators for exercise therapy. Making exercise therapy fun, convenient, and social could be important to helping youth "stick to" their prescribed exercise therapy.

CAUTION: Inconsistent reporting and heterogeneity of adherence constructs and measurement across the existing evidence may influence the validity of these findings. More research is needed to fully understand how to improve exercise therapy adherence in youth with musculoskeletal conditions.

STUDY DETAILS

AUTHOR CONTRIBUTIONS: We declare that all authors were fully involved in the study and preparation of the manuscript. All authors have read and approved the final manuscript.

DATA SHARING: All data sets not included in the online appendices are available from the corresponding author on reasonable request.

PATIENT AND PUBLIC INVOLVEMENT: No patients or public partners were involved in this research.

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Maria Tan during the development of the search strategy for this research. This study was conducted on Treaty 6 territory (a traditional gathering place for diverse Indigenous peoples, including the Cree, Blackfoot, Metis, Nakota Sioux, Iroquois, Dene, Ojibway/Saulteaux/Anishinaabe, and Inuit), as well as the unceded territory of the Coast Salish Peoples, including the territories of the xʷməlkʷəyəm (Musqueam), Skwxwú7mesh (Squamish), and Stó:lō and Səlilwətaʔ/Selilwitulh (Tsleil-Waututh) Nations.

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SEARCH STRATEGY AND RESULTS

For all databases, Medical Subject Headings and key words were selected based on consultation with a library scientist and content experts from among the study team. Truncation and alternate spelling (ie, American and British) were utilized as appropriate for all key words, while subject headings were selected from available options, varying by database.

MEDLINE (Ovid)

1. exp Pediatrics/ or exp Adolescent/ or exp Child/
2. adolescen* OR youth* OR teen* OR child*
3. 1 or 2
4. exp Patient Compliance/ or exp Compliance/ or exp Patient Participation/ or exp Treatment Adherence/
5. adher* OR adhear* OR compliance OR fidelity OR participa* OR barrier* OR facilitator* OR behaviour change OR behavior change OR adopt* OR uptake OR congruence OR maintenance
6. 4 or 5
7. exp Exercise Therapy/ or exp Exercise Movement Techniques/ or exp Physical Conditioning, Human/
8. exercise therap* OR therapeutic exercise* OR exercise program* OR home program*
9. 7 or 8
10. 3 and 6 and 9

CINAHL

1. (MH "Adolescence+") OR (MH "Child+") OR (MH "Pediatrics+")
2. adolescen* OR youth* OR teen* OR child*
3. 1 or 2
4. (MH "Patient Compliance+") OR (MH "Behavioral Changes+")
5. adher* OR adhear* OR compliance OR fidelity OR participa* OR barrier* OR facilitator* OR "behaviour change" OR "behavior change" OR adopt* OR uptake OR congruence OR maintenance
6. 4 or 5
7. (MH "Therapeutic Exercise+")
8. "exercise therap*" OR "exercise program*" OR "therapeutic exercise*" OR "home program"
9. 7 or 8
10. 3 and 6 and 9

Scopus

1. adolescen* OR youth* OR teen* OR child*
2. adher* OR adhear* OR compliance OR fidelity OR participa* OR barrier* OR facilitator* OR "behaviour change" OR "behavior change" OR adopt* OR uptake OR congruence OR maintenance
3. "exercise therap*" OR "exercise program*" OR "therapeutic exercise*" OR "home program"
4. 1 and 2 and 3

SPORTDiscus

1. (DE "CHILDREN") OR (DE "YOUTH") OR (DE "TEENAGERS") OR (DE "PEDIATRICS")
2. adolescen* OR youth* OR teen* OR child*
3. 1 or 2
4. DE "EXERCISE adherence"
5. adher* OR adhear* OR compliance OR fidelity OR participa* OR barrier* OR facilitator* OR "behaviour change" OR "behavior change" OR adopt* OR uptake OR congruence OR maintenance
6. 4 or 5
7. DE "EXERCISE therapy" OR DE "EXERCISE therapy for children"
8. "exercise therap*" OR "therapeutic exercise*" OR "exercise program*" OR "home program"
9. 7 or 8
10. 3 and 6 and 9

[LITERATURE REVIEW]

APPENDIX A

PEDro

1. "children adherence exercise"
2. "adolescent adherence exercise"
3. "children adherence home program"
4. "adolescent adherence home program"

ProQuest

1. noft(adolescen* OR youth* OR teen* OR child*) AND noft(adher* OR adhear* OR compliance OR fidelity OR participa* OR barrier* OR facilitator* OR "behaviour change" OR "behavior change" OR adopt* OR uptake OR congruence OR maintenance) AND noft("exercise therap*" OR "therapeutic exercise*" OR "exercise program*" OR "home program*")

Results

Database/Date Searched	Results, n
MEDLINE	
June 28, 2018	3134
October 1, 2019	549
CINAHL	
June 28, 2018	1826
October 1, 2019	349
Scopus	
June 28, 2018	2331
October 1, 2019	344
SPORTDiscus	
June 28, 2018	413
October 1, 2019	99
PEDro	
June 28, 2018	41
October 1, 2019	6
ProQuest	
June 28, 2018	136
October 1, 2019	41
Total	9269

APPENDIX B

MIXED METHODS APPRAISAL TOOL SCORING GUIDE

Customized minimum scoring criteria for this review, organized by methodological category, to be used in conjunction with published 2018 Mixed Methods Appraisal Tool instructions (Hong et al³⁶).

1. Qualitative studies (including ethnography, phenomenology, narrative research, grounded theory, case study, and qualitative description)
 - 1.1. Is the qualitative approach appropriate to answer the research question?
 - *Minimum criteria:* describes the approach and rationale for using that method
 - 1.2. Are the qualitative data-collection methods adequate to address the research question?
 - *Minimum criteria:* refers to the process of how they sampled and collected data: sampling method, description of participants, interviewers, methods/data collection, location
 - 1.3. Are the findings adequately derived from the data?
 - *Minimum criteria:* reports and describes how data/theory was derived/analyzed (eg, what approaches they used to get their data: did they use inductive/deductive approaches? thematic analysis: how were theories derived?)
 - 1.4. Is the interpretation of results sufficiently substantiated by data?
 - *Minimum criteria:* interpretation/themes supported by data, such as quotations. Reports or defines data "saturation" or data/theoretical sufficiency (eg, sampling will cease once theoretical or data sufficiency has been achieved. This will be achieved once sufficient data are collected to be able to represent how participants constructed their lives and worlds after this experience and a meaningful reflection of reality is achieved. Or, once a convincing theory or explanation can be confidently verified from the data with no gaps or pitfalls, confidence in theoretical sufficiency has been obtained)
 - 1.5. Is there coherence between qualitative data sources, collection, analysis, and interpretation?
 - *Minimum criteria:* approach should result in desired outcome of study design (eg, if doing qualitative description, should not end up in a theory; if using grounded theory, theory should be provided; if looking at a phenomenology, should describe the phenomena)
2. Quantitative randomized controlled trials
 - 2.1. Is randomization appropriately performed?
 - *Minimum criteria:* describes randomization process and allocation concealment
 - 2.2. Are the groups comparable at baseline?
 - *Minimum criteria:* baseline demographics/characteristics are provided (eg, provides a table with baseline characteristics)
 - 2.3. Are there complete outcome data?
 - *Minimum criteria:* randomized controlled trial reports greater than 80% complete data, or dropout rate less than 20%
 - 2.4. Are outcome assessors blinded to the intervention provided?
 - *Minimum criteria:* outcome assessors are blinded. Ideally, attempts are also made to blind the interventionists where possible, or reports why they could not blind
 - 2.5. Did the participants adhere to the assigned intervention?
 - *Minimum criteria:* 80% of the people follow through on their group allocation. Examples of poor group adherence include greater than 20% crossover from one group/intervention to the other, or reported adherence rates for the intervention are less than 80%
3. Quantitative nonrandomized studies (including nonrandomized controlled trials, cohort studies, case-control studies, and cross-sectional analytic studies)
 - 3.1. Are the participants representative of the target population?
 - *Minimum criteria:* inclusion/exclusion criteria reported. Who, where, and how they recruited/sampled are described
 - 3.2. Are measurements appropriate regarding both the outcome and intervention (or exposure)?
 - *Minimum criteria:* reports validity and reliability of outcome of interest, explanation of appropriate measures and justified tools (penalize for lazy reporting)
 - 3.3. Are there complete outcome data?
 - *Minimum criteria:* at least 80% enrolled contribute to outcome of interest
 - 3.4. Are the confounders accounted for in the design and analysis?
 - *Minimum criteria:* controls confounders in some way, such as study design (matched pairing) or analyses (multivariable analyses, stratified data)
 - 3.5. During the study period, is the intervention administered (or exposure occurred) as intended?
 - *Minimum criteria:* greater than 80% of the people follow through on their intervention or remain in the exposure group. If not reported, it is zero
4. Quantitative descriptive studies (including incidence or prevalence study without comparison group, surveys, case series, and case reports)
 - 4.1. Is the sampling strategy relevant to address the research question?
 - *Minimum criteria:* the source of the sample is relevant to the target population

APPENDIX B

- 4.2. Is the sample representative of the target population?
 - *Minimum criteria:* inclusion/exclusion criteria are described. Adequate sampling procedure/population
- 4.3. Are the measurements appropriate?
 - *Minimum criteria:* explanation of appropriate measures and justified tools, describes the validity and reliability of the tools
- 4.4. Is the risk of nonresponse bias low?
 - *Minimum criteria:* includes completed data greater than 80%
- 4.5. Is the statistical analysis appropriate to answer the research question?
 - *Minimum criteria:* consistency in the descriptive and inferential statistics (eg, consistency between using parametric/nonparametric data, matching should be paired *t* tests, or reports met the assumptions for the tests). If no statistical analyses were reported, automatic "no"
5. Mixed-methods studies (including convergent design, sequential explanatory design, sequential exploratory design)
 - 5.1. Is there an adequate rationale for using a mixed-methods design to address the research question?
 - *Minimum criteria:* provides a rationale for why they used mixed methods (eg, comprehensive understanding)
 - 5.2. Are the different components of the study effectively integrated to answer the research question?
 - *Minimum criteria:* describes appropriate steps to integrate components into one cohesive product
 - 5.3. Are the outputs of the integration of qualitative and quantitative components adequately interpreted?
 - *Minimum criteria:* do the inferences (outputs) make sense given the 2 components?
 - 5.4. Are divergences and inconsistencies between quantitative and qualitative results adequately addressed?
 - *Minimum criteria:* divergences are reported and explained
 - 5.5. Do the different components of the study adhere to the quality criteria of each tradition of the methods involved?
 - *Minimum criteria:* rates all 3 sections (qualitative, quantitative, mixed methods), reporting the lowest score

CHARACTERISTICS OF INCLUDED STUDIES

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
<i>Qualitative Studies</i>							
De Monte et al ¹⁸ Australia Phenomenology 5/5	JIA (n = 13) Female, n = 11 (85%) Age, 11 y (8-16 y)	To (1) understand the children's perspective of living with JIA and (2) understand how this had an impact on their participation in home exercise programs	NR	NR NA NR	1: Lack of understanding the importance of exercise/long-term benefits 11: A number of children (n = 7) commented that they had better things to do than exercises 6: Time was another significant issue for not participating in exercises. It was reported that both being too busy with other things and having too many exercises to complete were considerations 3: One child reported that, "Because I'm just too lazy" (Lisa, 12 y), she did not get the required exercises done 9: Boredom with the repetitive nature of some exercises was a common theme that made them less appealing to do 9: The children discussed the pain caused by arthritis, which had an impact on their participation in home exercise programs	5: The group setting was identified as a positive experience to meet other children with arthritis and a fun medium to enable the completion of exercises 6: For some children (n = 3), their exercise programs were incorporated into their school routines, with the assistance of a teacher aide 9: Another reported facilitator of exercises was making them fun 10: Finally, rewards, such as a sticker and lollies, appeared to be a motivator for many children to complete their exercises. Although the children reported that they did not get these all the time, it became apparent that they were given them at times when participation was limited to improve motivation	NA
Evans and Hardy ²⁴ United Kingdom Qualitative case study 4/5	Sports injuries (torn ACL, dislocated shoulder) (n = 2) All male Age, 19 ± 0 y	To derive cross-case summaries from case study profiles to enhance the interpretability and meaningfulness of the findings emerging from the goal-setting intervention study	Mixed NR	NR	11: Goal setting: self-selected versus surgeon 11: Goal setting: demotivating if it was not successful 9: Slow progress equaled frustration	8: Diary keeping increased confidence	NR
Birt et al ⁸ United Kingdom Phenomenology 4/5	Joint hypermobility (n = 19) Female, n = 10 (53%) Age, 12.6 y (9-17 y)	To enhance understanding of the factors underlying concordance with a multidisciplinary treatment program for joint hypermobility in children	Mixed None 7 12 wk	NR NA NR NR	8: Child not taking responsibility for completing exercise 10: Unsupervised setting 6: Lack of time and physical resources 4: Lack of privacy 9: Monotony of exercise	5: Parent supervision 6: Building the exercises into daily family routines 10: Activities as consequential rewards for completion 9: Fun exercises 9: Competition with others (family) 5: Completing exercises together with family 9: Experienced a physical improvement, which in turn created motivation to continue with the exercises	NR

Table continues on page B6.

APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Hutzel et al ³⁹ Canada Phenomenology 4/5	JIA (n = 4) All female Age, NR	To identify elements of a successful community-based exercise program for children with arthritis by investigating the perspectives of fitness instructors who led the program	Aerobic Partial 3 45-55 min 12 wk	NR	3: Children who could not keep up with their healthy peers often entered the program with little confidence in their physical abilities 6: The children had homework burden and social responsibilities that acted as obstacles to integrating the exercise program into their lives 4: They relied on family members to take them to class and encourage them to exercise at home. This assistance was often limited by family routines	6: Exercise schedule, integrating exercise into their lifestyle 10: Follow-up in class or on phone 11: Formation of activity goals 4: Community centers were better than hospitals for this type of program 5: Parental and peer support: parental encouragement seemed to influence children's participation in class and at home 9: Healthy sense of competition during the classes 5: Some children were inspired by the sports and activities others with JIA performed	7: The instructors taught children techniques to help them participate maximally in the sessions, such as decreasing the excursion in sore joints, reducing exercise intensity, changing the pace, or avoiding exercising painful joints 10: The instructors felt that close monitoring and feedback were essential to children's success 9: Instructors motivated the children to participate by choosing music they liked, giving imaginative names to the exercises, and creating class competitions

Table continues on page B7.

APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Kashikar-Zuck et al ⁴⁴ United States Qualitative case study 3/5	Juvenile fibromyalgia (n = 17) All female Age, 16 ± 2.15 y (12-18 y)	To (1) obtain information about the feasibility, safety, and tolerability of the 8-wk (16-session) group-based FIT Teens intervention for adolescents with juvenile fibromyalgia, and (2) gather detailed feedback from participants about their impressions of the acceptability, format, and content of the program	Motor control Full 2 30 min 8 wk	NR NR Class register Session attendance	6: Timing of session (unwillingness to miss school) 4: Transportation issues	5: Group format allowed them to motivate one another 3: "Not just being forced to do traditional physical therapy ... with this being catered toward people with fibromyalgia. I was thinking that if she can do it, then I can do it, too" 6: "I need some sort of a plan. So this was helpful how it is always scheduled same day, same time" 5: Therapeutic alliance: "I get the concept, but I forget the positioning exactly. So then they [exercise physiologist and psychologist] would right away be like, 'Okay, here.' It was never like, 'Why would you forget something like that?' ... they were really helpful" 4 and 7: "At the end of it, she gave us this program [handouts] so we can keep on going.... I think I'll do really well with them. We got the BOSU [balance trainer device] and ... a packet of exercises [to take home]" 8: Nearly all participants reported that the pace and progression of learning exercises were a positive feature, and the majority reported that the interventionists appropriately modified the exercises as needed to meet individual levels of ability 5: Group: participants were unanimously positive about the group format, mainly due to the supportive and encouraging group environment and the opportunity to meet other patients with juvenile fibromyalgia 5: Peer support: "I really liked being with the other girls ... I never knew they were going through the same things or ... the same problems ... knowing someone else feels the same way you do really helped" 5: Peer support: "We were able to see how they were doing [the exercises] and encourage each other. The support was the biggest thing" 5: Peer support: "Getting to know other people with fibromyalgia around my age was nice" 5: Group: "I liked learning the exercises in a group format ... I liked knowing that I wasn't the only one confused or I wasn't the only one that wasn't that excited about learning this really complicated exercise" 5: Comparison: "[I] needed that reassurance for myself ... I saw that the other girls were fine with [exercises]. I was like, 'Okay, you are worrying over nothing'" 5: Group: "[I] wouldn't want to be doing it on my own ... because you wanna have other people in the group 'cause you know that there's other people out there that are just like you and you also learn from their experience"	8: Specific tailoring of program to individual 10: Review of diaries 4: Removal of financial barriers (reimbursement of transportation and class expenses) 9: Keep exercises pain free 6: Scheduling classes outside school hours 7: Provided written instructions 1: Education on the importance of exercise

Table continues on page B8.

APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Williams et al ⁹⁹ United Kingdom Qualitative case study 3/5	AIS (n = 6) All female Age, 14.3 ± 2.25 y (10-16 y)	To explore factors that influenced the acceptability and perception of the trial and interventions, issues influencing exercise adherence, and appropriateness of the chosen outcome measurement to participants of the exercise program	Motor control None 7 NR 26 wk	56% NR Self-reported exercise log Online exercise diary (monitored) Exercise frequency	6: Work hours of physical therapists (supervisors) 6: The children described the need to adjust their busy school routine to fit in the exercise 7: Complexity of exercise program difficult for children to "grasp"; however, the children did not describe the exercises as difficult to grasp 4: Lack of private space to exercise	6: Flexibility of schedule for supervised sessions 7: Reminder materials: children found the online diary useful as a reminder, particularly the videos. They confirmed that a paper copy could be a useful backup 10: "Someone checking up on me" (parent or physical therapist) was an incentive to keep going (SMS text messaging was most helpful) 8: Signing a contract helped motivate some children to participate ("grown-up aspect" was enjoyable) 11: Goal setting was possibly helpful, but many children did not remember participating 5: Peer support through existing social media sites was possibly helpful 8: Patient choice	5: Online chat forum (social support, access to clinicians for questions) 8: Exercise contract 10: Monitored exercise diary
Sims-Gould et al ⁸³ Canada Qualitative 3/5	JIA (n = 17) Female, n = 8 (47%) Age, 9.9-16.4 y	To describe perceived barriers to and facilitators of the uptake of and adherence to a 6-mo home-based exercise intervention for children diagnosed with JIA and their parents	Strength Partial 5 15-40 min 26 wk	NR 60% Self-reported exercise log Session completion	9: Children's dislike of the exercise intervention 6: Time pressures affected completion of exercise sessions 6: Total time required to complete exercise sessions 6: Exercise session scheduling conflicts due to school, extracurricular activities, and holidays/vacations 3: Forgetfulness 9: Pain 2: Injuries, illness that caused children to miss exercise sessions 11: Lack of prioritization 5: Group sessions (uncomfortable)	5: Parental support 5: Parent's knowledge 9: Enjoyment 5: Group exercise 9: Listening to music or watching TV while doing the exercises	NR
Neto et al ⁶⁴ Portugal Qualitative 3/5	Idiopathic neck pain (n = 21) Female, n = 12 (57%) Age, 17.43 ± 1.4 y	To explore the views of adolescents with chronic idiopathic neck pain toward an intervention consisting of pain neuroscience education and exercise administered in the school setting	Strength Full 1 15-30 min 3 wk	NR	NR	10: Technology as reminder	NR

Table continues on page B9.

APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
<i>Quantitative randomized studies</i>							
Mendonça et al ⁵⁹ Brazil RCT 5/5	JIA (n = 50) Female, n = 32 (64%) Age: intervention, 11.0 ± 3.9 y; control, 11.8 ± 3.4 y	To assess the effects of a Pilates exercise program on health-related quality of life in individuals with JIA	Mixed Full 2 50 min 24 wk	Control, 95%; intervention, 99% NR Self-reported exercise log (attendance frequency) Session attendance	NA	9: "Pilates exercises are more motivating" than traditional exercise	10: Physical therapists had frequent contact with patients' caregivers to encourage adherence 5: Caregiver involvement
Schreiber et al ⁸¹ Canada RCT 5/5	AIS (n = 50) Female, n = 47 (94%) Age, 13.4 ± 1.6 y	To determine the effect of a 6-mo Schroth PSSE intervention added to standard of care (observation or bracing) on the Cobb angle, compared to the standard of care alone, in patients with AIS	Mixed Partial 8 Supervised, 60 min; unsupervised, 30-45 min 26 wk	Supervised, 85%; unsupervised, 82.5% 70% Class register, self-reported exercise log (logbook) Session attendance, exercise frequency	6: Time constraint due to homework	NR	NR
Schreiber et al ⁸⁰ Canada RCT 5/5	AIS (n = 50) Female, n = 47 (94%) Age, 13.4 ± 1.6 y	To determine the effect of a 6-mo Schroth exercise intervention in conjunction with standard of care (observation and bracing) on quality of life, perceived appearance, and back muscle endurance, compared to the standard of care alone, in patients with AIS	Mixed Partial 8 Supervised, 60 min; unsupervised, 30-45 min 26 wk	Supervised, 85%; unsupervised, 82.5% 70% Class register, self-reported exercise logs (monitored) Session attendance, exercise frequency	NR	NR	4: Provided home equipment 4: Provided access to facilities 5: Promoted parental involvement. "When compliance dropped below 70%, we tried to resolve the issues cooperatively with patients and parents"
Wiegerinck et al ⁹⁷ the Netherlands RCT 4/5	Calcaneal apophysitis (n = 101) Female, n = 25 (25%) Age, 10.6 ± 1.6 y	To compare the effectiveness of 3 conservative treatment strategies for calcaneal apophysitis, with a decrease of pain being the primary outcome measure	Strength Partial 7 NR 12 wk	NR	NR	NR	1: Clearly explaining the expected results at onset

Table continues on page B10.

APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Tarakci et al ⁹¹ Turkey RCT 4/5	JIA (n = 81) Female, n = 37 (46%) Age: intervention, 10.02 ± 3.44 y (5-17 y); control, 10.82 ± 4.00 y (5-16 y)	To investigate the effects of an individually planned land-based home exercise program on pain, functional ability, and quality of life, using a randomized controlled single-blind design	Mixed Full 4 20-45 min 12 wk	≥75% NR Self-reported exercise log (monitored exercise diary for completion) Exercise frequency	4: Transportation difficulty (geographic location too far from hospital) 7: Paper handout only (no videos provided)	NR	7: Gradual increase of quantity of exercise program (number of exercises, repetitions, total time) 6: Reduced number of exercises 7: Demonstration by physical therapist 8: Individualization of program 1: Education to patient and parent (unexpected responses with respect to exercise training and joint protection, how the recommended exercise program may help them, and specific information about how to exercise safely and effectively and how to recognize postexercise soreness) 10: Compliance diary reviewed weekly 8: Individualization
Fanucchi et al ²⁶ South Africa RCT 4/5	Low back pain (n = 72) Female, n = 33 (46%) Age: intervention, 12 ± 0.7 y (12-13 y); control, 12 ± 0.7 y (12-13 y)	To determine whether an 8-wk exercise program would reduce the intensity and prevalence of low back pain in 12-to-13-year-old children, and would decrease the childhood physical risk factors for low back pain and promote a sense of well-being	NR Partial 4 Supervised, 40-45 min; unsupervised, NR 8 wk	Supervised, 87%; unsupervised, 33% Supervised, full attendance; unsupervised, ≥3 times per week Class register, self-reported exercise log Session attendance, exercise frequency	NR	9: Enjoyment 9: Symptom relief: "felt that the exercises helped to make them feel better" 9: Functional improvement: "make their backs feel stronger"	1: A physical therapist discussed the importance of the exercises the children would be doing and how the exercises related to their low back pain

Table continues on page B11.

APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Singh-Grewal et al ⁸⁴ Canada RCT 4/5	JIA (n = 80) Female, n = 64 (80%) Age: intervention, 11.7 ± 2.5 y (8-16 y); control, 11.5 ± 2.4 y (8-16 y)	To examine the effectiveness of a high-intensity 12-wk program in terms of submaximal oxygen consumption in children with inflammatory arthritis and to determine the effectiveness of this program in terms of self-reported physical function, peak oxygen consumption, and peak power	Aerobic Partial 3 45-55 min 12 wk	Intervention, 56%; control, 78% Attended >70% of training sessions and achieved heart rates of >75% of maximum heart rate in >50% of sessions Self-report exercise log (diary), objective measure (intermittent heart rate monitor) Sessions completed, exercise intensity	6: Lack of time	7: Less intense exercise regimen	10: Instructors maintained frequent contact 10: Children were rewarded with stickers for completed sessions and were able to trade these for small gifts 7: Videotaped instructions
Monticone et al ⁶¹ Italy RCT 4/5	AIS (n = 110) Female, n = 80 (73%) Age: intervention, 12.5 ± 1.1 y; control, 12.4 ± 1.1 y	To compare an innovative outpatient program combining active self-correction, task-oriented exercises, and education with a routinely followed program of traditional exercises to verify whether it could reduce spinal deformities and improve health-related quality of life in adolescents with mild AIS	Mixed Partial 3 Supervised, 60 min; unsupervised, 30 min Until maturity (approximately 40 mo/160 wk)	NR NR Self-reported exercise log (diary) Sessions completed	NR	NR	10: Diary checked weekly 5: Parent support 1: Education about condition 1: Education on purpose of exercise 7: Graded exposure to exercise/activity
Epps et al ²² United Kingdom RCT 4/5	JIA (n = 78) Female, n = 43 (55%) Age: intervention, 12 y (6-19 y); control, 11 y (4-19 y)	To compare the effects of combined hydrotherapy and land-based physical therapy with land-based physical therapy alone on cost, health-related quality of life, and outcome of disease in children with JIA	Mixed Full 8 60 min 10 wk	NR "Acceptable": NR NR NR	4: Didn't like chlorine 6: Found the hydrotherapy pool inconvenient to travel to 9: Didn't feel that it worked 4: Equipment/facility problems 3: Changing into swimsuit 9: Boring	4: Easier than land-based exercise 9: Less painful than land-based exercise 9: Fun and enjoyable	NR

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APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Stephens et al ⁸⁸ Canada RCT (pilot) 4/5	Fibromyalgia (n = 30) Female, n = 22 (73%) Age: intervention, 13.6 ± 1.8 y (12-13 y); control, 12.9 ± 2.7 y (12-13 y)	To determine the feasibility of performing an RCT to study the effects of an aerobic fitness program; feasibility was defined by program adherence and recruitment ability. The secondary purpose was to determine the effect of aerobic training on physical fitness (as defined by peak aerobic capacity, muscular power, and metabolic efficiency), fibromyalgia symptoms, and overall physical function in children with fibromyalgia	Aerobic Partial 3 40 min 12 wk	Overall, 64%; intervention, 67%; control, 61% "Acceptable": NR Class register, self-reported exercise log (diary) Objective measure (heart rate monitor), session attendance, sessions completed, exercise intensity (objective)	4: Lack of transportation 6: Lack of time 9: Lack of enjoyment of program	NR	5: Small instructor-patient ratio (1:4) to ensure adequate attention 7: Video program for home exercises 10: Frequent contact with patients and families through phone to motivate the children and solve potential impediments to participation 10: Children were rewarded with a sticker for each completed exercise session and were able to trade them for small token incentives
Rathleff et al ¹⁶ Denmark Cluster RCT 3/5	PFP (n = 121) Female, n = 97 (80%) Age, 17.2 ± 1.0 y (15-19 y)	To investigate the effect of exercise therapy as an add-on therapy to patient education, compared with education alone, on self-reported recovery	Mixed Partial 3 Supervised, NR; unsupervised, 15 min Supervised, 12 wk; unsupervised, 104 wk	Supervised, 20%; unsupervised, 36%; total, 26% Supervised, ≥80% attendance at prescribed sessions; unsupervised, exercising on ≥70% of available days Class register, self-reported exercise log, session attendance Exercise frequency	NR	NR	10: Regular SMS reminders and follow-up 5: Parent involvement 4: School-based exercise sessions 8: Multiple choices for timing
Riel et al ⁷⁷ Denmark RCT 3/5	PFP (n = 40) Female, n = 35 (88%) Age: intervention, 16.9 ± 1.5 y; control, 16.5 ± 1.5 y	To investigate whether real-time feedback on contraction time during exercises would improve the ability to perform the exercises with the prescribed contraction time per repetition, compared with no feedback on contraction time, among adolescents with PFP during a 6-wk intervention	Strength Partial 3 NR 6 wk	Feedback (intervention), 35.4%; no feedback (control), 20.3% NR Objective measure (app to measure total contraction time, divided by total prescribed time) Exercise time	NR	10: Feedback on contraction time	1: Participants told that compliance to exercises was important and would improve their odds of recovery

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APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Zapata et al ¹⁰³ United States RCT 3/5	AIS (n = 34) Female, n = 29 (85%) Age, 14.9 y	To investigate whether 8 wk of weekly supervised spinal stabilization exercises would reduce pain intensity, disability, and functional limitations and improve back muscle endurance in patients with AIS and low back pain, as compared with 8 wk of an unsupervised home exercise program	Mixed Partial 3 25 min 8 wk	Intervention, 95%; control, 67% NR Self-reported exercise logs, interview (verbal report) Session completion	NR	6: Decreasing home exercise program to as few exercises as possible seemed to promote compliance 10: Regular contact (supervised session) promoted improved compliance	9: The exercises were designed to be challenging, fun, and recognizable to promote motivation and adherence to the treatment regimen 7: DVD of exercises was provided to participants 10: Exercise log signed by parents
Habers et al ²⁹ the Netherlands RCT 2/5	Juvenile dermatomyositis (n = 26) Female, n = 16 (62%) Median age: intervention, 11.6 y (8.3-17.5 y); control, 12.6 y (8.7-17.6 y)	To study the feasibility, safety, and efficacy of an individually tailored 12-wk home-based exercise training program in the largest group of patients with juvenile dermatomyositis studied to date	Mixed Partial 2.5 40-60 min 12 wk	94% Self-report exercise log Objective measure (heart rate monitor) Sessions completed Exercise intensity (objective measure)	6: Other sport activities 6: Holiday 2: Fatigue 2: Illness 2: Transient physical complaints 4: Home-based exercise	4: Home-based exercise	8: Individually tailored program 4: Provided equipment 7: Provided detailed description of program
Eng and Pierzynowski ²¹ Canada RCT 1/5	PFP (n = 20) All female Age, 14.8 ± 1.2 y (13-17 y)	To evaluate the effectiveness of an 8-wk program of foot orthotics combined with exercise in adolescent female patients with diagnosed bilateral PFP	Mixed None 14 NR 8 wk	NR Reported performance of exercises the previous day on 3 random phone calls Interview (self-report on phone call) Sessions completed	NR	NR	10: Regular check-in phone calls

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APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Sule and Fontaine ⁸⁹ United States RCT 1/5	JIA (n = 33) Female, n = 11 (33%) Age: intervention, 14.0 ± 3.3 y; control, 16.1 ± 2.8 y	To assess the safety, feasibility, and effects of slow-speed resistance exercise in children with polyarticular JIA	Strength (intervention), aerobic (control) Full (intervention), none (control) 2 (intervention), 3 (control) NR (intervention), 30 min (control) 12 wk	29% (intervention), 12% (control) NR Self-reported (interview) Sessions per week	4: Having to travel to clinic for exercise sessions	NR	10: Monthly phone calls to assess compliance 6: Sessions available evenings and weekends
<i>Quantitative nonrandomized studies</i>							
Rivett et al ⁷⁸ South Africa Pre-experimental 3/5	Idiopathic scoliosis (n = 51) Sex and age, NR	To determine the effect of compliance to the Rigo System Cheneau brace and a specific exercise program on idiopathic scoliosis curvature, and to compare the quality of life and psychological traits of compliant and noncompliant subjects	Mixed None 5 25 min >52 wk	Compliant (intervention), 78.4%; noncompliant (control), 34.2% Exercising ≥3 d/wk Self-reported exercise log (diary) Exercise frequency	3: Personality traits: emotional instability and low ego strength	3: Personality traits: emotional stability, control, and high ego strength	7: Written explanations and pictures provided 10: Diary validated with parents 1: Discussion of consequences of noncompliance
Hedayati et al ³² Iran Quasi-experimental 3/5	Idiopathic scoliosis (n = 30) All female Age, 13.17 y (8-17 y)	To evaluate the impact of group exercise and adjustment of the in-brace force at shorter intervals (twice per week) on Cobb angle and quality of life, compared with independent exercise and routine brace adjustment (every 3 mo), in patients with idiopathic scoliosis	NR Full NR 120 min 11 wk	NR Missing >2 supervised sessions, exercising <6 h/wk at home (total not given, so cannot calculate percentages) NR NR	NR	8: Matching patients to preferred treatment (patient choice)	5: Group exercise to promote compliance

Table continues on page B15.

APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Rathleff et al ⁷⁵ Denmark Pre-experimental 3/5	PFP (n = 20) Female, n = 16 (80%) Age, 14.6 ± 1.1 y	To explore adherence to exercise therapy and to use the patient-reported outcomes to inform a sample-size calculation for a definitive trial	Mixed Partial 7 Supervised, NR; unsupervised, 15 min 13 wk	Supervised, 41%; unsupervised, 50% Supervised, 80% Supervised, class roster; unsupervised, self-reported exercise log (training log) Session attendance, sessions completed	NR	Home exercise preferred over clinic exercise due to 6: Less time-intensive nature 4: Lower cost 4: Ease of implementation 8: Patient choice	5: Parent involvement 10: Regular communication through phone or e-mail 10: Reminder texts the day before 6: Flexible exercise schedule
Negrini et al ⁶³ Italy Longitudinal observational study 3/5	AIS (n = 293) Female, n = 219 (75%) Age, NR	To investigate whether PSSEs could stop the progression and/or avoid bracing for those with AIS and at high risk for bracing (ie, 11-208 curves and Risser sign of 0-2), as compared with usual physical therapy or observation only	Mixed Partial 2-7 15-45 min >52 wk	NR NR Self-report Sessions completed, minutes exercising	NR	NR	8: Individualization 10: Checking in 5: Personal trainer as caregiver
Feldman et al ²⁷ Canada Prospective cohort study 2/5	JIA (n = 175) Female, n = 120 (69%) Age, 10.2 ± 4.4 y (2-18 y)	To determine whether adherence to treatment in children with JIA was associated with better clinical, functional, and quality-of-life outcomes	NR	54.2%-64.1% NR Existing measurement scale (PARQ) Behavioral component	9: Pain during exercise	2: Younger age 8: Child involvement in responsibility for treatment 1: Higher perceived helpfulness of the treatment (all discussed in this paper but identified in companion paper)	NR
Zapata et al ¹⁰² United States Prospective pre/post design 2/5	Hyperkyphosis (n = 14) Female, n = 5 at completion (36%) Age, 15.3 ± 2.0 y	To assess factors regarding adherence to an app-based exercise program in adolescents with hyperkyphosis and back pain after one-time exercise treatment followed by a 6-mo app-based home exercise program	Mixed None 3 15 min 26 wk	NR NR Self-report, app data Session completion	Cannot differentiate between barriers to exercise and barriers to app use	5: Social participation 9: Pain relief 11: Goal setting 5: Parent involvement 10: Exercise reminders (texts) 9: Fun	10: Check in at 2 wk 5: Instructions to reach out if any questions (support)

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APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
April et al ² Canada Cross-sectional study 1/5	JIA (n = 50) Female, n = 41 (82%) Age, 12.67 ± 2.68 y (8-18 y)	To determine the level of agreement between children with JIA and their parents regarding the child's adherence to treatment, for both medication and exercises, and to explore whether factors such as age, disease duration, and disease severity are associated with this agreement	NR	61.2% (children), 57.4% (parents) NR Existing measurement scales (PARQ and CARQ) Behavioral component	1: Negative feelings toward exercises	5: Performing exercises with parents 2: Younger age if parents were the ones recording adherence	NA
Rathleff et al ⁷³ Denmark Pre-experimental 1/5	PFP (n = 20) Female, n = 18 (90%) Age, 17 y (15-19 y)	To determine whether it is feasible to use the exercise-monitoring system connected to a tablet device to measure exercise adherence and dosage among adolescents with PFP	Strength Partial 3 NR 6 wk	15% of total time under tension prescribed NR Objective measure (app data) Self-reported exercise log (diary) Exercise frequency	10: Adequate feedback during supervised sessions	NR	1: Participants told that compliance to exercises was important and would improve their odds of recovery
Marais et al ⁵⁵ South Africa Pre-experimental 1/5	Subtalar overpronation (n = 20) Sex and age, NR	To investigate the hypothesis that strengthening the tibialis posterior muscle will decrease subtalar overpronation angles	Strength Partial 5 20-30 min 4 wk	NR NR Class register, self-reported exercise logs Session attendance, session completion	6: School obligations 6: Recreational activities 11: Personal priorities	NR	NR
Kwan et al ⁴⁹ China Prospective historical cohort-matched study 1/5	AIS (n = 48) Female, n = 38 (79%) Age: intervention, 12.3 ± 1.4 y (10-14 y); control, 11.8 ± 1.1 y (10-14 y)	To assess prospectively the effect of Schroth exercise on curve progression, appearance, and quality of life in patients with AIS and high-risk curves during bracing	Mixed Partial 7.5 Supervised, 60 min; unsupervised, NR Supervised, 8 wk; unsupervised, NR	54% of intervention group were found to be compliant with exercise >80% attendance of therapy sessions and completion of the prescribed home exercise program at least 5/7 d/wk Class register, self-reported exercise logs (monitored) Session attendance, sessions completed	NR	NR	6: Reduced number and length of sessions from previous protocols to find "compromise between maintaining adequate supervision and minimizing disruption to the patients' and families' lives" 10: Exercise log verified by parents

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APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
Carman et al ¹² United States Quasi-experimental 1/5	Idiopathic scoliosis (n = 45) All female Age: intervention, 13.42 y (12.08-15.33 y); control, 12.58 y (10.5-13.92 y)	To evaluate prospectively whether a closely monitored physical therapy exercise program, performed in association with Milwaukee brace wear for treatment of scoliosis, had any effect on outcome	Motor control None 2 30-120 min NR	NR Rated “good” or “excellent” exercise frequency and quality by physical therapist at 3-to-4-mo check-up visit, using arbitrary scale Health care professional interview (arbitrary scoring system by physical therapist for quality and frequency at 3-to-4-mo check-up) Exercise replication	NR	NR	7: Exercise handout
Klepper et al ⁴⁸ United States Within-subject interrupted time series 1/5	JRA (n = 25) Female, n = 23 (92%) Age: female, 12 y (8-17 y); male, 14 y (12-16 y)	To investigate the effects of an 8-wk weight-bearing physical conditioning program on disease signs and symptoms in children with JRA	Aerobic Partial 3 60 min 8 wk	NR “Acceptable”: must have completed at least 18/24 available sessions (75%) to be included Class register, self-reported exercise log, session attendance Sessions completed	9: Pain during exercise	NR	5: Allowed to have friend exercise with them 10: Parents required to sign activity records 10: Rewards and incentives for completion 7: Gradual increase in exercise intensity and duration 7: Careful instruction and monitoring by exercise leaders to ensure safety 8: Individualization of videos 9: Music during exercise
Zapata et al ¹⁰¹ United States Prospective cohort 1/5	AIS (n = 33) Female, n = 26 (79%) Age, 15.1 ± 2.0 y	To assess whether the Schroth-based method is effective in skeletally immature participants with mild AIS curves at high risk of progression, compared with the standard of care of observation (control), in reducing curve magnitude, curve progression, and brace prescription after 1 y of intervention	Mixed None 3 15 min 52 wk	58%-80% NR E-mail survey Total days exercised, total minutes exercised	NR	5: Parental involvement	5: Booster sessions as needed (offer of support)

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APPENDIX C

Study Features ^a	Sample ^b	Aim of Study	Intervention Details ^c	Adherence Concepts ^d	Barriers to Adherence (theme, data item) ^e	Facilitators of Adherence (theme, data item) ^e	Strategies to Improve Adherence (theme, data item) ^e
<i>Quantitative descriptive studies</i>							
Singh-Grewal et al ⁸⁵ Canada Case series (pilot) 3/5	JIA (n = 9) Female, n = 5 (56%) Age, 9.4 y (8.9-11.1 y)	To assess the safety and feasibility of laboratory-based exercise testing in children with JIA	Mixed Full 2 NR 12 wk	63% "Acceptable": NR Class register Session attendance	4: Long travel times 6: Family time constraints 9: Pain/worsening symptoms	9: Enjoyment (pool more than gym) 5: Interactions with instructors 10: Small rewards for attendance 6: Scheduling during evenings and weekends 6: Duration and frequency	7: Gradual increase in exercise intensity and duration
Wibmer et al ⁹⁶ Austria Case series 2/5	AIS (n = 8) All female Age, 10.7 y (7.8-13.2 y)	To determine whether an exergame could improve motivation and correct performance of the specific exercises prescribed to treat juvenile idiopathic scoliosis and AIS	Mixed None 5 30 min 24 wk	32.5% 180 sessions completed Objective measure (game software: number of sessions, playing time) Sessions completed	9: Bored of exercises if continued for "too long" 7: No progression of difficulty	10: Immediate feedback 9: Playful diversion 9: Encouragement to improve "score" (within and between sessions)	NR
Dovelle et al ¹⁹ United States Case study 2/5	Flexor tendon repair of the finger (n = 1) Female Age, 8 y	To report on a young girl who received a secondary tendon repair made with a free tendon graft, and whose hand was subsequently rehabilitated under the Washington Regimen of early controlled motion	Mixed None 7 NR 12 wk	NR NR Interview Sessions completed	NR	8: Therapists should offer reasonable alternatives, therapist should remain flexible in approach to patient treatment 5: Establish a positive patient-therapist relationship from the very beginning of therapy	1: Education on importance of exercise to recovery 5: Family involvement
Lafont ⁵⁰ United States Case study (dissertation) 1/5	ACL repair (n = 1) Female Age, 16 y	To examine the viability of BFR training as a treatment modality in the postoperative management and rehabilitation of an ACL reconstruction and meniscus repair in a young female soccer player	Strength Partial 2-7 45-60 min 8 wk	NR NR Attendance Sessions per week	NR	NR	1: Education on the importance of adherence

Abbreviations: ACL, anterior cruciate ligament; AIS, adolescent idiopathic scoliosis; BFR, blood flow restriction; CARQ, Child Adherence Report Questionnaire; FIT, Fibromyalgia Integrative Training; JIA, juvenile idiopathic arthritis; JRA, juvenile rheumatoid arthritis; NA, not applicable; NR, not reported; PARQ, Parent Adherence Report Questionnaire; PFP, patellofemoral pain; PSSE, physiotherapeutic scoliosis-specific exercise; RCT, randomized controlled trial; SMS, short message service.

^aAuthor, country, design, and Mixed Methods Appraisal Tool quality rating. Ratings are from 0 to 5, with 0 indicating poor quality and 5 indicating excellent quality.

^bAge is reported as mean, mean $\pm$ SD, or mean (range) unless otherwise indicated.

^cType of exercise, supervision, sessions per week, minutes per session, and program length.

^dRate (percentage of prescribed), target (percentage of prescribed), measurement tool, and outcome.

^eThemes: 1, Beliefs; 2, Physical characteristics; 3, Psychological characteristics; 4, Physical environment; 5, Social environment; 6, Time; 7, Program details; 8, Patient engagement; 9, Experience during exercise; 10, Reinforcement; 11, Goals.

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A Secondary Injury Prevention Program May Decrease Contralateral Anterior Cruciate Ligament Injuries in Female Athletes: 2-Year Injury Rates in the ACL-SPORTS Randomized Controlled Trial

The incidence of primary anterior cruciate ligament reconstruction (ACLR) has increased 77% in women and 19% in men over a 12-year period.⁹ Female athletes have a higher incidence of anterior cruciate ligament (ACL) injuries in the comparable sports of basketball, soccer, and lacrosse² than male athletes. Athletes who return to cutting and pivoting sports after ACLR have increased odds of graft

rupture and contralateral injury compared to those who return to less strenuous sports.⁴⁸ Up to 1 in 3 athletes who return to sport (RTS) may sustain a second ACL

injury, and nearly half of those second injuries occur within 2 months of returning to sport.¹⁹ Female athletes have a higher contralateral injury rate compared to male athletes,^{31,32,46} with the reported risk of a contralateral ACL injury as much as 6 times higher compared to male athletes (26% versus 5%, respectively).³¹

While younger athletes are more likely to return to their preinjury levels of sport,^{4,21,48} athletes younger than 20 years of age have 6 times increased odds of a graft rupture and 3 times increased odds of a contralateral tear compared to older athletes.⁴⁸ A systematic review of athletes aged 6 to 19 years and undergoing ACLR found an overall second ACL injury rate of 27%.²¹ Young female athletes have an even higher rate of second ACL injury,³⁹ up to 32%.⁴⁶

When an important marker of success (return to their previous level of sport) is also a key risk factor for second ACL injury, clearly there is a need for targeted secondary ACL injury prevention and

● **OBJECTIVE:** To determine whether the addition of perturbation training to a secondary injury prevention program reduces the rate of second anterior cruciate ligament (ACL) injury compared to the prevention program alone.

● **DESIGN:** Single-blinded randomized controlled trial.

● **METHODS:** Thirty-nine female athletes who intended to return to cutting/pivoting sports were enrolled 3 to 9 months after primary anterior cruciate ligament reconstruction (ACLR). Athletes were randomized to receive a training program of either progressive strengthening, agility, plyometrics, and prevention (SAPP) (n = 20) or SAPP plus perturbation training (n = 19); each had 10 sessions over 5 weeks. Occurrence and side of

second ACL injury were recorded for 2 years after primary ACLR.

● **RESULTS:** There were 9 second ACL injuries in the 2 years after ACLR. There was no statistically significant difference in rate or side of second ACL injury between the SAPP-plus-perturbation training and SAPP groups.

● **CONCLUSION:** Adding perturbation training to a secondary ACL injury prevention program did not affect the rate of second ACL injury in female athletes. *J Orthop Sports Phys Ther* 2020;50(9):523-530. Epub 1 Aug 2020. doi:10.2519/jospt.2020.9407

● **KEY WORDS:** ACL, female athletes, perturbation, return to sport, secondary injury prevention, young athletes

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RTS training. Current clinical practice guidelines for primary prevention of knee and ACL injuries⁵ recommend preventative training programs that include a combination of neuromuscular training, strengthening, balance, and proximal control exercises.⁴² The most effective postoperative training programs for returning to preinjury level of function and reducing the risk of reinjury include quadriceps strengthening and neuromuscular training for 9 to 12 months.^{18,22,45} Neuromuscular training techniques, such as perturbation training designed to induce compensatory changes in muscle activation patterns and facilitate dynamic joint stability,³⁷ improve self-reported knee function more than strength training alone in the first 6 months after ACLR.³⁶ Perturbation training improves knee stability through adaptations in neuromuscular control via potential destabilizing activities about the knee.¹⁵ It is unclear how female athletes respond to postoperative perturbation training.

The Anterior Cruciate Ligament-Specialized Post-Operative Return To Sports (ACL-SPORTS) training program is a sport-specific secondary ACL injury prevention program.⁴⁹ The ACL-SPORTS program includes progressive strengthening, agility, plyometrics, and prevention (SAPP) exercises. The program is effective for preventing secondary ACL injury in men, with only 1 graft rupture in 40 male athletes.⁶ However, the effects of secondary ACL injury prevention in women have yet to be explored.

The purpose of this study was to determine whether adding perturbation training to a secondary injury prevention program would be more effective than the prevention program alone in reducing second ACL injury rates in female athletes after ACLR. We hypothesized that female athletes who received perturbation training in addition to the second injury prevention program would have fewer graft ruptures and fewer contralateral ACL injuries compared to those who received the prevention program alone.

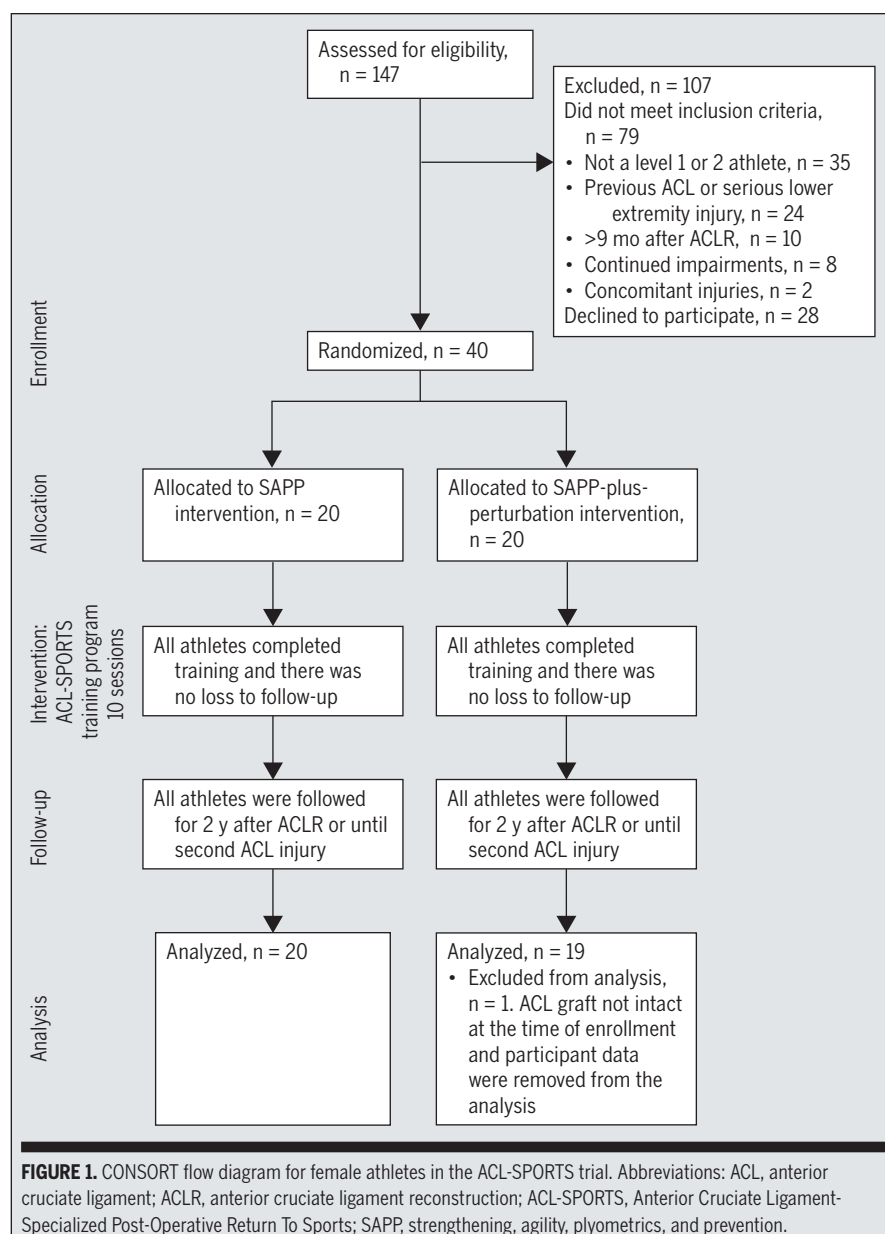
METHODS

WHITE ET AL⁴⁹ PREVIOUSLY PUBLISHED the methods of the ACL-SPORTS single-blinded randomized controlled trial, which was approved by the University of Delaware Institutional Review Board and registered at www.ClinicalTrials.gov (NCT01773317). This analysis is part of the a priori secondary outcomes for this trial. Prior to enrollment, all athletes gave written consent (or assent when younger

than 18 years of age, with parent/guardian consent). The CONSORT diagram is in **FIGURE 1**. This analysis addressed outcomes deemed important by patients.

Participants

Participants were recruited from the local community through physician and physical therapist referral, newspaper and flyer advertisements, and word of mouth, with 40 female athletes enrolled from December 2011 through January 2017 via 17 surgeons. Selection criteria were (1) aged



13 to 55 years, (2) planned return to a cutting/pivoting/jumping sport for more than 50 hours per year, (3) no previous ACL injury, and (4) no history of other major lower extremity injury/surgery. Participants were required to have a unilateral ACLR, with no grade III concomitant ligament injuries or cartilage defects larger than 1 cm².

Surgical technique, graft choice, and rehabilitation prior to enrollment were not controlled. At enrollment, participants were screened by a physical therapist and had no knee pain, minimal to no knee effusion, and full knee range of motion. They had ACLR less than 9 months prior, had a quadriceps index (QI) of 80% or greater, initiated a running progression, and had not yet returned to level 1 or 2 sport. Athletes were randomized to receive either SAPP training or SAPP plus perturbation using a random number generator by a research coordinator (Martha Callahan). All researchers performing data collection were blinded.

All participants completed training. However, the data from 1 athlete (SAPP plus perturbation training) who may not have had an intact ACL graft at enrollment were excluded from the analysis. All participants were required to pass objective RTS criteria.^{19,49} Participants returned to the clinic at 1 and 2 years after surgery for functional and clinical testing and patient-reported outcomes. Those who were unable to return in person at

2 years (n = 3) were contacted by phone. Self-reported second ACL injury status was collected for all 39 participants, as well as time from surgery to RTS, time from surgery to second ACL injury, and time from RTS to second ACL injury. Additionally, 100% of participants returned to sport by 2 years, 87% at their preinjury level of sport.¹¹

Training

Training occurred twice a week for 5 weeks under the supervision of a physical therapist at the University of Delaware Physical Therapy Clinic. Perturbation exercises used a platform/roller board combination, unilateral stance on a roller board, and unilateral stance on a tilt board, each with therapist perturbations in multiple planes (FIGURE 2); a full list and description of all training exercises can be found in White et al.⁴⁹ Training also included education and cuing for correct technique of all exercises, especially to avoid valgus collapse during landings. Progression was determined according to soreness and effusion guidelines.^{1,13,49} All participants were required to pass the following RTS criteria before beginning RTS: 90% or greater on the QI and on 4 single-legged hop limb symmetry indices, scores of 90% or greater on the Knee Outcome Survey-Activities of Daily Living Scale (KOS-ADLS) and a single-item global rating of perceived knee function (GRS), and surgeon approval.

Age

Because younger age at primary ACL injury increases the risk of a second injury,^{21,39,46,48} we divided the athletes into groups of those under 25, those under 20, and those under 18 years of age.

Statistics

We compared rate and side of second ACL injury between the 2 groups using chi-square tests of proportions, and time from primary surgery to second ACL injury using independent *t* tests ($\alpha = .05$), performed in SPSS statistical software (IBM Corporation, Armonk, NY). To compare our study to previously published literature, we categorized the rate and side of second ACL injury by age, independent of group assignment, and calculated chi-square tests of proportions for each age category. Power was calculated a priori for the primary outcomes of the trial (biomechanical and clinical and functional outcomes), and the study was adequately powered.⁴⁹

RESULTS

THIRTY-NINE FEMALE ATHLETES were enrolled between December 2011 and January 2017. There were no differences in any demographics between groups at enrollment (TABLE 1).

Second ACL Injury

There were 9 second ACL injuries within 2 years of ACLR in the female participants



FIGURE 2. Perturbation exercises performed by the SAPP-plus-perturbation group. (A) Platform and roller board, (B) unilateral roller board, and (C) unilateral tilt board. Abbreviation: SAPP, strengthening, agility, plyometrics, and prevention.

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in the ACL-SPORTS trial: 4 graft ruptures and 5 contralateral injuries, for an overall second ACL injury rate of 23% (TABLE 2). All second ACL injuries occurred in athletes with a hamstring autograft. There were no group differences in rate ($P = .77$) or side ($P = .25$) of second ACL injury, thus the groups were collapsed for additional comparisons. Post hoc analysis revealed an effect size of $w = 0.047$ for a power of $(1 - \beta) = 0.059$.

Age

The second ACL injuries by age are in TABLE 3. Eight of the second ACL injuries occurred in female athletes younger than 18 years of age at primary surgery; all 9 occurred in those younger than 20 years of age at primary surgery. However, there was no statistically significant difference in rate of second ACL injury by age category. Results by age, with comparison to previous literature, are in TABLE 4.

DISCUSSION

THE PURPOSE OF THIS SECONDARY outcomes analysis was to determine whether adding perturbation training to a second injury prevention program would be more effective than the prevention program alone in reducing second ACL injury rates in female athletes after ACLR. There was no statistically significant difference in rate or side of second ACL injury between those who received SAPP plus perturbation training and those who received SAPP alone, so we collapsed the groups to determine any differences in outcomes from our injury prevention program compared to the existing literature.

Graft Rupture

The graft rupture rate in our study is comparable to, or slightly higher than, previous research (see TABLE 4 for comparisons). There are many risk factors for graft rupture, including younger age at primary injury,^{21,39,46,48} return to a cutting/pivoting/jumping sport,^{44,48} and graft type.^{26,28,34} Almost half the athletes in our study had a hamstring autograft, and all graft ruptures occurred in those with a hamstring graft; Paterno et al^{31,32} did not report graft types. Hamstring grafts have slightly higher rates of failure than bone-patellar tendon-bone grafts.^{34,35,38} Athletes who had ACLR with hamstring autografts achieved impairment resolution earlier and returned to sports, on average, 4 months earlier than those with bone-patellar tendon-bone autografts. Therefore, biological healing may have played a role in the graft failure.⁴⁰ Because age, time to RTS, and rate of return to cutting/pivoting sports were comparable, possible differences in graft selection may account for the differences between our athletes and those reported by Paterno et al.^{31,32}

Contralateral Injury

The contralateral ACL injury rate in our study was lower than or comparable to previous research (see TABLE 4 for comparisons). The lower rates of contralateral ACL injuries may be due to the bilateral

TABLE 1

DEMOGRAPHICS OF PARTICIPANTS AT ENROLLMENT^a

	SAPP (n = 20)	SAPP Plus Perturbation (n = 19)	P Value
Age at primary surgery, y	18.9 ± 5.8 (14.0-53.7)	19.0 ± 8.8 (12.7 ^b -54.0)	.99
Height at enrollment, m	1.65 ± 0.06	1.65 ± 0.08	.82
Weight at enrollment, kg	68.8 ± 10.9	67.9 ± 14.3	.83
Graft type, n			.32
Patellar tendon autograft	8	8	
Hamstring autograft	8	10	
Allograft	4	1	
Time from surgery to passing RTS criteria, wk	37.0 ± 11.4 (18.4-63.0)	37.0 ± 12.1 (20.3-54.0)	.99

Abbreviations: RTS, return to sport; SAPP, strengthening, agility, plyometrics, and prevention.

^aValues are mean ± SD or mean ± SD (range) unless otherwise indicated.

^bThis participant was 13.5 years of age at enrollment.

TABLE 2

GROUP COMPARISONS FOR OUTCOMES^a

	SAPP (n = 20)	SAPP Plus Perturbation (n = 19)	P Value
Second ACL injury, n (%)	5 (25)	4 (21)	.77
Side of second ACL injury, n (%)			.25
Contralateral	4 (20)	1 (5)	
Graft rupture	1 (5)	3 (16)	
Mechanism of second ACL injury, n			...
Noncontact	3	4	
Contralateral	2	1	
Graft rupture	1	3	
Direct contact (contralateral)	1	...	
Contact to body (contralateral)	1	...	
Time from surgery to second ACL injury, wk	50.3 ± 6.6 (42.3-56.6)	69.9 ± 24.8 (34.7-87.7)	.13
Time from passing RTS criteria to second ACL injury, wk	19.4 ± 4.45 (14.14-21.72)	40.9 ± 24.7 (14.14-62.14)	.09

Abbreviations: ACL, anterior cruciate ligament; RTS, return to sport; SAPP, strengthening, agility, plyometrics, and prevention.

^aValues are mean ± SD (range) unless otherwise indicated.

training in the ACL-SPORTS training program: all agility drills and a majority of the plyometric and strengthening activities were performed in both limbs. Similar altered movement patterns and impairments predict primary and secondary ACL injuries.^{8,20,33} If poor mechanics and movement patterns were at fault in primary ACL injury, then there might have been similar mechanics and movement patterns in the contralateral limb. Additionally, the uninvolved limb may also develop altered mechanics as compensation for the injured limb.^{10,29,50} Neuromuscular training can improve impairments^{7,37} and movement patterns.^{12,27} The ACL-SPORTS training emphasis on proper landing technique and movement patterns during agilities, plyometrics, and performance activities bilaterally⁴⁹ may explain the lower contralateral injury rate in our study.

Return to Sport

Because athletes in our study had the highest rate of RTS (100% returned to sport, 87% to their preinjury level¹¹) reported in the literature,^{4,48} they also had greater sports exposure and, subsequently,

higher risk of second ACL injury.^{44,48} Yet, the rate of second ACL injury in our study was not higher than that found in previous research.^{46,48} Webster and Feller⁴⁶ and Webster et al⁴⁸ did not report the rate of returning to cutting/pivoting sports, and Paterno et al,^{31,32} Webster and Feller,⁴⁶ and Webster et al⁴⁷ did not report any control of their participants' rehabilitation. Thus, the similarities in injury rates across different studies may reflect a positive effect of our intervention.

Postsurgical Follow-up

We registered new injuries in the first 2 years after ACLR. Over half of all second injuries occur in the first year after ACLR,^{46,48} and more than three quarters

occur within 2 years of surgery.⁴⁶ Minimal differences in rates of second injury from 1 to 2 years after RTS have been reported,^{31,32} with a mean time from RTS to second injury of 7.0 months.³² In the female athletes of the ACL-SPORTS trial, average time from surgery to RTS was 8.5 months, giving an average follow-up of 15.5 months after RTS. Therefore, our 2-year registration period should be sufficient to capture most second ACL injuries in our cohort.

RTS Criteria

Passing RTS criteria can reduce risk of second ACL injury,^{14,19,24} but there is conflicting evidence about the efficacy and impact of these criteria.^{25,30} All athletes

TABLE 3

RATES OF SECOND ACL INJURY BY AGE^a

Age Group	Graft Rupture	Contralateral ACL	Overall	P Value
<25 y (n = 35)	4 (11.4)	5 (14.3)	9 (25.7)	.25
<20 y (n = 32)	4 (12.5)	5 (15.6)	9 (28.1)	.11
<18 y (n = 26)	3 (11.5)	5 (19.2)	8 (30.8)	.11

Abbreviation: ACL, anterior cruciate ligament.

^aValues are n (percent) unless otherwise indicated.

TABLE 4

COMPARISON BETWEEN RATES OF SECOND INJURY FOR FEMALE ATHLETES IN THE ACL-SPORTS TRIAL AND THOSE IN PREVIOUS LITERATURE, MATCHED BY AGE

	<25 y			<20 y		<18 y	
	ACL-SPORTS	Paterno et al ³¹	Paterno et al ³²	ACL-SPORTS	Webster and Feller ⁴⁶	ACL-SPORTS	Webster and Feller ⁴⁶
Sample size (female only), n	35	42	59	32	116	26	85 ^a
Overall second injury rate	22.8%	33.3%	32.2%	28.1%	29%	30.8%	31.8%
Graft rupture	11.4%	7.1%	8.5%	12.5%	12%	11.5%	12.9%
Contralateral rupture	14.3% ^b	26.2%	23.7%	15.6%	17%	19.2%	18.8%
Surgeon/physical therapist clearance for RTS?	Yes	Yes	Yes	Yes	NR	Yes	NR
Objective RTS criteria?	Yes	No	No	Yes	Variable	Yes	Variable
Follow-up time	2 y after ACLR	1 y after RTS	2 y after RTS ^c	2 y after ACLR	5 y after ACLR ^d	2 y after ACLR	5 y after ACLR ^d
Time from surgery to RTS ^e	8.8 ± 2.6	NR	8.3 ± 2.0	8.8 ± 2.6	NR	8.7 ± 2.7	NR

Abbreviations: ACLR, anterior cruciate ligament reconstruction; ACL-SPORTS, Anterior Cruciate Ligament-Specialized Post-Operative Return To Sports; NR, not reported; RTS, return to sport.

^aPersonal communication from Kate Webster, November 5, 2019.

^b11.4% without contact injuries.

^cApproximately 32.3 months.

^dValue is mean (range, 3-10 years).

^eValues are mean ± SD months.

in the ACL-SPORTS trial were required to have surgeon approval for RTS and pass objective criteria: 90% or greater on the QI and on 4 single-legged hop limb symmetry indices, and scores of 90% or greater on the KOS-ADLS and a single-item GRS. In the cohorts reported by Paterno et al,^{31,32} athletes were required to have surgeon and physical therapist approval for RTS, but did not have to meet any objective criteria before release. The study cohort reported by Webster and Feller⁴⁶ had to pass running and squatting criteria, but the authors did not provide objective thresholds for passing.

While we cannot separate the impact of our RTS criteria on rate of second ACL injury from the impact of the training program, these findings suggest that the ACL-SPORTS training program's objective RTS criteria may reduce risk of second ACL injury in female athletes. However, it is not enough to reduce the risk of second ACL injury in our youngest female athletes.

Clinical Implications

The reduction in contralateral ACL injury rate in our female athletes compared to other published research is promising, especially with an easy-to-implement training program. However, our overall second injury rate of 23.1% is still much too high to believe we have addressed the needs of our athletes. While the ACL-SPORTS training was highly effective in reducing second ACL injury rates in male athletes (1 second injury in 40 athletes),⁶ it was not as effective in female athletes. Current rehabilitation programs are not meeting all the needs of female athletes, particularly those under 18 years of age. High compliance with a neuromuscular training program is associated with a lower rate of ACL injuries in female athletes.⁴³ Higher volume and more frequent, longer-duration sessions are effective for primary knee injury prevention.⁴¹ However, 10 sessions over 5 weeks, as in our study, may not maximize the benefits of training for female athletes. Addition-

al research on longer, higher-intensity, more frequent secondary prevention programs for female athletes is needed, as well as research on the influence of types of feedback^{16,17} and psychological readiness to RTS.^{3,23,47}

Strengths and Limitations

A strength of this study is our sample. We recruited from a variety of surgeons, and participants had postoperative rehabilitation at multiple physical therapy clinics, making our results generalizable. Reasonable enrollment criteria ensured that all participants entered the study at an appropriate point to begin the RTS progression, without being overly burdensome.

Athletes self-reported RTS and level of participation, and we did not assess number of athletic exposures (practices/games). Because all athletes were required to meet RTS criteria, we are unable to separate the effects of the training program from the RTS criteria. Additionally, while a majority of second ACL injuries occur within 2 years of ACLR, 2 years may not be sufficient to capture the true rate of contralateral ACL injuries, which may occur later after ACLR.

While our sample of 39 is small, type II error is unlikely. Post hoc analysis revealed an effect size of $w = 0.047$ for a power of $(1 - \beta) = 0.059$. We would have needed more than 3000 participants to be adequately powered to detect a between-group difference.

CONCLUSION

WHILE THE ADDITION OF PERTURBATION training to a secondary injury prevention program does not seem to have benefits for female athletes, the participants in the ACL-SPORTS training program reported fewer contralateral injuries compared to previously published results. ●

KEY POINTS

FINDINGS: The addition of perturbation training did not affect the rate of second

anterior cruciate ligament (ACL) injury in female athletes.

IMPLICATIONS: The common core elements of the Anterior Cruciate Ligament-Specialized Post-Operative Return To Sports training program (progressive strength, agility, plyometrics, and prevention [SAPP]) may reduce the risk of contralateral ACL injury in female athletes as part of an easily implemented return-to-sport training program.

CAUTION: We had a small sample and assessed second injury up to 2 years after primary ACL reconstruction, which may not be long enough to capture all secondary injuries. Additionally, we did not evaluate or control for athletic exposures.

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors made substantial contributions to the conception or design of the work, or the acquisition, analysis, or interpretation of data for the work; drafted the work or revised it critically for important intellectual content; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work to ensure that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

DATA SHARING: Summary data relevant to this study are included in this article, with full data available on request from the study's primary investigator, Dr Snyder-Mackler (smack@udel.edu). Please include how proposed data will be used.

PATIENT AND PUBLIC INVOLVEMENT: This analysis addressed outcomes deemed important by patients.

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Who's Afraid of the Big Bad Wolf? Open-Chain Exercises After Anterior Cruciate Ligament Reconstruction

Fewer than half of athletes meet quadriceps strength symmetry goals when they are cleared to return to sport after anterior cruciate ligament reconstruction (ACLR).¹³ Why, then, do we as rehabilitation professionals fail to help our patients restore quadriceps function? Overwhelming evidence links quadriceps strength with essential outcomes: normal walking and running gait, function, self-reported success, return to sport, subsequent knee injury, and long-term progression of knee osteoarthritis.⁵ We argue that pervasive misinformation and antiquated beliefs about the safety of open-chain exercises are direct obstacles to improving quadriceps strength after ACLR.

Practice Patterns That Are Based on Fairy Tales

The fairy tale of “The Three Little Pigs” illustrates our view of the obstacles to best practice. The fairy tale tells of a confrontation between 3 pigs and a big bad wolf, and asks: “Who’s afraid of the big bad wolf?” The first 2 pigs chose to build their homes out of straw or sticks, which the wolf easily blew down. The third pig built a house of brick that the wolf was unable to destroy.

There are many ways to interpret the story; we liken the wolf to quadriceps muscle weakness. The house of straw is

the belief that open-kinetic-chain exercises are unsafe and result in loosening of the anterior cruciate ligament (ACL) graft. The house of sticks is the assumption that only closed-kinetic-chain exercises are functional, and therefore are sufficient for good outcomes. Both of these beliefs (ie, houses) fall when the big bad wolf huffs and puffs with evidence to the contrary.

By contrast, the brick house is built on 3 evidence-based statements about open-kinetic-chain exercises: they are (1) safe, (2) critical to restoring quadriceps strength, and (3) key for assessing readiness to return to sport. The brick house can repel the big bad wolf of protracted quadriceps muscle weakness.

The House Built of Straw: Open-Kinetic-Chain Exercises Loosen ACL Grafts

One of the most common fears is that open-chain exercises loosen the healing

ACL graft because of high strain on the graft. Some of the earliest reports warning against the use of open-chain exercises¹⁵ focused on displacement and strain in either ACL-deficient knees or in those with a grade II strain, in low knee flexion angles.¹⁵ These results were refuted later in the 1990s.⁴ With every step, strain on the ACL is 2 to 3 times the strain of open-chain knee extension with 30 Nm of extension torque at 15° of knee flexion.²

The house of straw had, unfortunately, already been built, with the early authors suggesting a total focus on closed-chain exercise and avoiding open-chain exercises.¹⁰ A recent review thoroughly analyzed 10 randomized trials and, challenging the straw house, found no systematic evidence of a difference in anterior tibial laxity between those who performed open- versus closed-chain exercises after ACLR.⁹

Despite overwhelming evidence to the contrary, fear of loosening the healing graft has become so ingrained that contemporary clinicians often accept this disproven fear as fact, passing both the fear and associated quadriceps weakness on to their patients. And the perpetuation of this dogma continues; recent clinical practice guidelines from a major medical journal advocated delaying open-chain exercises for at least 4 weeks after surgery,¹⁴ citing no evidentiary support for why they should not be introduced sooner.

● **SYNOPSIS:** Restoring quadriceps muscle strength is integral to recovery following an anterior cruciate ligament reconstruction. We argue that clinicians should re-evaluate their beliefs about open-chain exercises and measure this important

variable to improve outcomes for their patients. *J Orthop Sports Phys Ther* 2020;50(9):473-475. doi:10.2519/jospt.2020.0609

● **KEY WORDS:** kinetic-chain exercise, quadriceps, rehabilitation, return to sport

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The House Built of Sticks: Closed-Kinetic-Chain Exercises Are More Functional Than Open-Kinetic-Chain Exercises

The house of sticks is built on a foundational belief that the best recovery will occur only when patients perform exercises that replicate the types of activities in which they will re-engage. Closed-chain exercises involve the entire lower extremity, and patients are able to compensate for weak quadriceps with other muscle groups (eg, hip extensors when performing a leg press). Closed-chain exercises do little to combat the ubiquitous quadriceps weakness that may persist for at least 2 years after surgery.⁵

Adding open-chain exercises may result in stronger quadriceps and a higher percentage of athletes returning to sport than closed-chain exercises alone. We contend that, when properly loaded, open-chain exercise for the quadriceps will have a direct positive impact on patient outcomes.

An unfortunate consequence of the straw and stick houses is a dearth of equipment to train and measure quadriceps strength. Many clinics no longer have open-chain knee extension machines and attempt to simulate the effect by using either bands or body resistance exercises. The only way to isolate and generate appropriate quadriceps load is to use a knee extension machine or electromechanical dynamometer, where progressive resistance can be applied.

The stick house has also been built without any tools to quantify quadriceps strength impairments, with the belief that these data are not functional or relevant to the athlete's ability to perform on the field. Fewer than half of physical therapists may use any form of instrumented strength testing.¹ Most concerning is that nearly half may not measure strength at all—instead inferring quadriceps strength from other measures, such as hop testing.¹ Hop tests overestimate recovery compared to isokinetic quadriceps strength testing.⁶ The risk is that clinicians assume patients have met criteria for rehabilitation progression or discharge, when they have not.

The closest approximation to the “gold reference standard” (electromechanical dynamometer) of quadriceps strength testing is a 1-repetition-maximum test on a knee extension machine.¹¹ Leg presses and handheld dynamometers secured with a stabilization strap overestimate the strength of the involved quadriceps muscle. Again, clinicians risk assuming that patients have met criteria for rehabilitation progression or discharge, when they have not. A danger is that the patients are discharged and/or return to sport based on an artificially high quadriceps index.¹¹ Closed-chain strength testing is a poor surrogate for measuring quadriceps strength. We implore the community to strengthen their houses by using some form of an electromechanical dynamometer or a 1-repetition-maximum test on a knee extension machine to assess quadriceps strength throughout rehabilitation and for return-to-sport decisions.

The House Built of Bricks: Open-Kinetic-Chain Exercises Are Necessary for Full Recovery and Improved Function

Quadriceps muscle recovery can only occur if the quadriceps are directly targeted during rehabilitation. There are negative changes in neurological signaling to the quadriceps and in muscle physiology^{8,12} after an ACL rupture and ACLR. The loss of the native ACL also results in muscle inhibition at multiple levels of the nervous system.⁷ Negative adaptations that occur within the quadriceps muscle include expansion of the extracellular matrix, fiber-type switching, and fewer satellite cells.⁸ Altering these negative changes can only come about through isolating the muscle, using techniques that elicit a strong activation to facilitate muscle regeneration and motor recruitment.

We advocate using electric stimulation to facilitate greater recruitment and reverse muscle inhibition soon after injury and surgery.³ When coupled with open-chain exercises, electric stimulation yielded superior results to those of closed-chain exercises.³ We urge clinicians to re-evaluate their perceptions

by following the evidence. Certainly, functional exercises are important components of rehabilitation after ACLR. However, higher-level functional training and running should only commence from a solid quadriceps strength foundation.

As clinicians build and strengthen the brick house together, we suggest revisiting how clinicians dose open-chain exercises. Early in rehabilitation, low loads to the point of muscle failure are appropriate. As the patient progresses, resistance must increase to at least 60% to 70% of the 1-repetition maximum. Clinicians' knowledge of the healing response and where the graft is under the most strain will guide appropriate rehabilitation progression. If patients are working their muscles close to failure, then rest between sets and days is critical, as this is the time that the muscle repairs and hypertrophies.

Summary

If rehabilitation clinicians do not emphasize regaining quadriceps strength, do not measure it, and steer patients away from doing open-chain exercises, they are failing their patients. By quelling fears of open-chain exercise, clinicians are better placed to help patients avoid poor outcomes.

We aim to stimulate greater dialog and reflection on the dogma that open-chain exercises are not safe. They are.⁴ We encourage clinicians to fearlessly incorporate open-chain exercises into their rehabilitation programs. Most importantly, we strongly encourage clinicians to shore up their brick house foundations: measure quadriceps strength and underscore to patients how important it is to regain quadriceps strength.

Key Points

- Open-chain exercises following ACLR are safe.
- Open-chain exercises are the only means to isolate the quadriceps.
- Electromechanical dynamometers or a 1-repetition-maximum test using a knee extension machine are the preferred methods to evaluate recovery of quadriceps muscle strength. ●

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors made substantial contributions to the conception, design, and drafting of the article and revised it critically for important intellectual content. All authors assume responsibility for the work.

DATA SHARING: All data relevant to the Viewpoint are included in the article.

PATIENT AND PUBLIC INVOLVEMENT: There was no patient-public involvement in the development of this Viewpoint.

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Meniscus or Cartilage Injury at the Time of Anterior Cruciate Ligament Tear Is Associated With Worse Prognosis for Patient-Reported Outcome 2 to 10 Years After Anterior Cruciate Ligament Injury: A Systematic Review

● **OBJECTIVES:** (1) To assess prognostic factors for patient-reported outcome measures (PROMs) and physical activity 2 to 10 years after anterior cruciate ligament reconstruction (ACLR) or anterior cruciate ligament (ACL) injury, and (2) to assess differences in prognostic factors between patients treated with ACLR and with rehabilitation alone.

● **DESIGN:** Prognosis systematic review.

● **LITERATURE SEARCH:** Systematic searches were performed in PubMed, Web of Science, and SPORTDiscus.

● **STUDY SELECTION CRITERIA:** We selected prospective cohort studies and randomized clinical trials that included adults or adolescents undergoing either ACLR or rehabilitation alone after ACL rupture. Studies had to assess the statistical association between potential prognostic factors (factors related to patient characteristics, injury, or knee symptoms/function measured at baseline or within 1 year) and outcomes (PROMs and physical activity).

● **DATA SYNTHESIS:** Our search yielded 997 references. Twenty studies met the inclusion criteria.

Seven studies with low or moderate risk of bias remained for data synthesis.

● **RESULTS:** Moderate-certainty evidence indicated that concomitant meniscus and cartilage injuries were prognostic factors for worse PROMs 2 to 10 years after ACLR. Very low-certainty evidence suggested that body mass index, smoking, and baseline PROMs were prognostic factors for worse outcome. Very low-certainty evidence suggested that female sex and a worse baseline Marx Activity Rating Scale score were prognostic factors for a worse Marx Activity Rating Scale score 2 to 10 years after ACLR. There was a lack of studies on prognostic factors after rehabilitation alone.

● **CONCLUSION:** Concomitant meniscus and cartilage injuries were prognostic factors for worse long-term PROMs after ACLR. The certainty was very low for other prognostic factors. *J Orthop Sports Phys Ther* 2020;50(9):490-502. Epub 1 Aug 2020. doi:10.2519/jospt.2020.9451

● **KEY WORDS:** knee surgery, ligament, prognosis, sporting injuries

Anterior cruciate ligament (ACL) injuries have serious negative long-term consequences, such as lower extremity dysfunction, low levels of physical activity, poor quality of life, and early development of knee osteoarthritis (OA).^{3,7,15,21,25,50,53} Resolving impairments and returning to sport are often the main short-term goals for patients.^{6,7} Clinicians must consider the long-term consequences of ACL injury when providing patient education and making decisions about interventions early after injury or reconstruction.⁵⁵ There is a need for high-quality studies on prognostic factors for important long-term outcomes, such as patient-reported outcome measures (PROMs), levels of physical activity, and OA.

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A prognosis study can aim to predict the total individual risk, given all available information in a prediction model, or to estimate the average causal effect of an exposure or treatment on an outcome in a population, given adjustment for relevant confounders. Both approaches may provide important information on prognostic factors, as a prognostic factor can be either causally or noncausally related to an outcome variable.^{32,62,73} Many systematic reviews have evaluated prognostic factors for developing knee OA after ACL injury.^{42,45,53,67,69,70} A few systematic reviews have reported prognostic factors for long-term PROMs and level of physical activity,^{4,16,19,45,46,67} but half of them were of poor quality due to lack of risk of bias assessments.^{45,46,67} Also, patients treated with rehabilitation alone have not been included in previous systematic reviews.

Consequently, a high-quality systematic review on prognostic factors for PROMs and level of physical activity 2 to 10 years after ACL reconstruction or injury, with an appropriate and thorough risk of bias assessment, is needed. Such a study could provide information about prognostic factors that can be targeted with early treatment, and thereby help to improve outcomes for patients with ACL injury.

Current evidence suggests similar clinical courses following rehabilitation alone and ACL reconstruction,^{2,23-26,48} but we do not know whether prognostic factors differ in the 2 treatment groups. There is great clinical interest to identify early prognostic factors associated with better outcome after both ACL reconstruction and rehabilitation alone. This knowledge can help inform treatment choices. No systematic review has previously addressed this topic.

Therefore, the aims of our systematic review were (1) to assess prognostic factors for PROMs and physical activity 2 to 10 years after ACL injury or ACL reconstruction, and (2) to assess differences in prognostic factors between patients treated with ACL reconstruction and those treated with rehabilitation alone.

METHODS

THIS SYSTEMATIC REVIEW WAS CONDUCTED according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.⁴⁹ Our study protocol was published in PROSPERO (CRD42018095602) on June 7, 2018.

Eligibility Criteria

Eligible studies met the following inclusion criteria: prospective cohort studies and randomized clinical trials that reported prognostic factors for PROMs or level of physical activity at a mean of 2 or more and less than 10 years in adults and adolescents (mean age, older than 13 years) undergoing either ACL reconstruction or rehabilitation alone after complete ACL rupture. Studies had to assess the association between exposure and outcome with regression analyses. Studies that exclusively reported on revision ACL reconstruction, knee dislocation, partial tear, or bilateral injury were excluded; those that reported on a subset of patients with these conditions were included. Prognostic factors were defined as patient characteristics (eg, age, sex, psychological factors), factors related to the injury (eg, concomitant injury), or knee symptoms and function (eg, functional performance, PROMs) that were assessed within 1 year after injury or ACL reconstruction.

The following PROMs were selected: the Knee injury and Osteoarthritis Outcome Score (KOOS), International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC-SKF), and Knee Outcome Survey-Activities of Daily Living Scale (KOS-ADLS). These PROMs were chosen based on their frequent use as stand-alone PROMs for long-term outcomes during the last decade, and because they have good measurement properties.^{5,13,37-39,58,71} The KOOS consists of 5 subscales: pain, other symptoms, function in daily living, function in sport and recreation (S/R), and knee-related quality of life (QoL).⁵⁸ The KOOS can

be reported as individual subscale scores or as the “KOOS-4,” which is an average score of 4 subscales (function in daily living excluded). The IKDC-SKF measures symptoms, function, and sports activity in patients with different types of knee problems.³⁷ The KOS-ADLS assesses the impact of symptoms on the ability of the patient to perform daily activities.³⁹ All 3 questionnaires are scored from 0 (worst) to 100 (best).

We included all outcomes that reflect type and level of physical activity, including the 3 components that define physical activity: frequency, intensity, and duration (eg, objective measures such as accelerometers, patient-reported physical activity questionnaires, and return to sport).¹⁰ An example of a PROM of physical activity for ACL-injured individuals is the Marx Activity Rating Scale. The Marx Activity Rating Scale is a brief survey on the frequency of participation in sports involving running, pivoting, cutting, and deceleration.⁴⁷

Data Sources and Searches

We systematically searched PubMed, Web of Science, and SPORTDiscus for articles published from database inception to September 20, 2018. The search strategy for PubMed is displayed in **TABLE 1**. Filters on “Humans” and “English language” were used, and all free-text words/terms were searched on “Title/abstract.” Relevant systematic reviews were identified with the same search terms in PubMed. Reference lists from systematic reviews and included studies were hand searched for relevant material to supplement electronic database searches. To identify additional literature, the following simplified search was performed in Google Scholar: “Anterior cruciate ligament”|ACL Prognosis|“Prognostic factors”|Predict|Associations “Return to sports”|Participation|“Activity level”|“Physical activity”|Tegner|Marx|KOOS|IKDC|KOS “Prospective study”|“Observational study”|“Cohort study”|RCT. The 100 first (and most relevant) results from Google Scholar were screened.

[LITERATURE REVIEW]

The searches were performed with assistance from and reviewed by librarians at the Norwegian School of Sport Sciences and the University of Oslo.

Study Selection and Data Extraction

Two independent researchers (M.P. and J.L.J.) screened for eligibility and extracted data with customized data-extraction forms. Covidence systematic review software (Veritas Health Innovation Ltd, Melbourne, Australia) was used to assist this process. Calibration exercises were performed to ensure consistency between reviewers, but without testing agreement. Discrepancies were resolved by discussion or a third reviewer (H.G. or M.A.R.). We contacted study authors to resolve uncertainties when necessary. Titles and abstracts were screened to identify potentially relevant studies for full-text eligibility assessment. The reasons for exclusion were recorded. When several exclusion criteria were fulfilled, the first reason on a predefined list was chosen.

Risk of Bias Assessment

Risk of bias was assessed with the Quality In Prognosis Studies (QUIPS) tool.²⁹ We chose this tool because it was developed specifically for the methodological assessment of prognostic studies. The QUIPS tool is reliable for systematically assessing risk of bias in the following 6 domains: study participation, study attrition, prognostic factor measurement, outcome measurement, study confounding, and statistical analysis and reporting.²⁹ Three independent reviewers (M.P., J.L.J., and K.M.) performed the scoring of the different domains. Our operationalization of the QUIPS items is described in supplemental material (available at www.jospt.org). For studies where the objective was prediction and not etiology, the confounding domain was classified as irrelevant (because the goal of a prediction model is to predict the total individual risk given all information, for example, independent of the covariates' influence on each other).^{32,62}

The overall risk of bias for each study was classified as follows: low when there was low risk of bias in all domains, moderate when there was moderate risk of bias in 1 or more domains, and high when there was high risk of bias in 1 or more domains.³³ For all domains, high risk of bias was defined as a level where the results of the study should not be trusted, and/or they were impossible to interpret due to research methodology and/or inadequate description of methodology. This was an overall assessment and decision, hence no study was classified as high risk of bias in any domain based on only 1 question.

Data Synthesis and Analysis

Results from all included studies (n = 20) are presented in supplemental material (available at www.jospt.org). We included only studies with low or moderate risk of bias in the data synthesis. The purpose was to ensure that conclusions and recommendations to clinicians and patients were robust, and to make the results easier to interpret and to translate into practice. When data from the same patients were used in publications on the same prognostic factors and outcomes at different time points, we included the most recent publication. Results were presented separately for PROMs, level of physical activity, and patients undergoing ACL reconstruction versus rehabilitation alone. When possible, results from studies on each treatment group were extracted separately. Results from adjusted analyses were preferred. It was not possible to perform a meta-analysis due to methodological diversity in outcome measures and follow-up times.

Certainty of evidence for each prognostic factor was judged as high, moderate, low, or very low according to the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach.^{34,36} We used GRADEpro GDT (Evidence Prime Inc, Hamilton, Canada) to help generate evidence summaries.

TABLE 1

PUBMED SEARCH

Search Term

- 1 Anterior cruciate ligament[MeSH terms] OR Anterior cruciate ligament injury[MeSH terms] OR Anterior cruciate ligament reconstruction[MeSH terms]
- 2 Anterior cruciate ligament OR ACL
- 3 Prognosis[MeSH terms]
- 4 Prognosis OR Prognostic factors OR Prognostic factor OR Predictor OR Predictors OR Predict OR Prediction OR Predictive OR Effect modifiers OR Effect modifier OR Risk factors OR Risk factor OR Factor OR Factors OR Associated OR Association OR Associations
- 5 Return to sport[MeSH terms]
- 6 Return to sport OR Return to sports OR Participation OR Activity level OR Physical activity OR "Tegner activity scale" OR "Marx activity rating scale" OR Return to play OR KOOS OR "Knee injury and Osteoarthritis Outcome score" OR "International Knee Documentation Committee subjective knee form" OR "IKDC-SKF 2000" OR IKDC-SKF2000 OR "International Knee Documentation Committee Subjective Knee Evaluation Form" OR "IKDC-SKF" OR "Knee Outcome Survey" OR KOS
- 7 Prospective studies[MeSH terms]
- 8 Prospective studies OR Prospective study OR Observational study OR Cohort study OR Randomized controlled trial OR Randomized clinical trial OR Randomised controlled trial OR Randomised clinical trial OR RCT OR Randomised trial OR Randomized trial
- 9 1 OR 2
- 10 3 OR 4
- 11 5 OR 6
- 12 7 OR 8
- 13 9 AND 10 AND 11 AND 12

RESULTS

Search Results

DATABASE SEARCHES IDENTIFIED 974 references, and 23 additional references were identified through bibliographies (n = 2), Google Scholar (n = 3), and reference lists (n = 18). After removing duplicates, 561 references remained. All were screened for eligibility, and 431 were ineligible due to objectives, outcome, or follow-up time. The remaining 130 articles were read in full text, and 20 met all eligibility criteria (FIGURE). Seventeen of the included studies were identified through the systematic search, while 3 were identified through other sources. Due to more recent publications on the same prognostic factors and outcomes, we excluded the results on concomitant cartilage lesions, but not meniscus lesions, from Røtterud et al,⁵⁹ and all results from Magnussen et al⁴³ from 2016. Seven studies with low or moderate risk of bias remained for data synthesis.^{1,22,27,44,59,64,68}

Study Characteristics

Characteristics of the included studies (n = 20) are presented in TABLE 2. Most of the cohort studies were based on data from the Multicenter Orthopaedic Outcomes Network (MOON) cohort (n = 8)^{9,14,17,43,44,64,65,72} and the Swedish and/or Norwegian Knee Ligament Registers (n = 5).^{1,8,27,59,68} In the included randomized clinical trials (RCTs), both treatment groups were treated as one cohort for the assessment of prognostic factors.^{18,22,56,61} Three of the RCT publications were based on the Knee Anterior Cruciate Ligament, Nonsurgical versus Surgical Treatment (KANON) trial.^{18,22,56} The studies included a median of 495 (Q1-Q3 range, 121-2333) patients. Because several publications involving the large registries reported on the same patients, it was challenging to estimate the total number of unique patients included in this systematic review. Most studies included patients undergoing primary ACL reconstruction only, and no study included only patients treated with rehabilitation

alone. Patients with substantial concomitant injuries^{8,14,18,22,27,40,43,44,51,56,61,63,65} and/or contralateral ACL injury^{14,17,27,59,61,64,65,68,72} were frequently excluded from the included studies. The median age at inclusion was 26 years (range, 18-27 years). The median percentage of women was 44% (range, 26%-77%). Preinjury activity level was reported in 7 studies, of which 4 studies^{17,40,51,63} included patients active in pivoting sports preinjury and 3 studies^{18,22,56} included patients with a Tegner activity scale score between 6 and 9 (6, recreational pivoting sports; 9, competitive sports).

Sixteen studies were etiologic^{1,9,14,17,18,22,27,40,43,44,56,59,61,63,65,68} and 4 were predictive.^{8,51,64,72} Among the studies included in our data synthesis, only Spindler et al⁶⁴ was a predictive study.

Risk of Bias

Risk of bias for the 6 QUIPS domains and an overall rating is shown in TABLE 3. Studies generally performed poorly on the domains “study confounding” and “statistical analysis and reporting,” because they did not explicitly state which covariates were adjusted for and why; did not separate between confounders, mediators, and colliders (and subsequently did not treat these covariates in accordance with existing rules for adjustment); or had mixed predictive and etiologic statistical approaches, which led to uninterpretable results.^{31,62,73}

Data Synthesis of Studies With Low or Moderate Risk of Bias (n = 7)

Prognostic Factors for PROMs in Patients Treated With ACL Reconstruction Prognostic factors for PROMs in patients treated with ACL reconstruction were assessed in 7 studies from 4 cohorts. The IKDC-SKF was an outcome in 2 studies^{44,64} and the KOOS was an outcome in 7 studies.^{1,22,27,44,59,64,68} The following 13 factors were assessed by 1 or more studies with low or moderate risk of bias: sex, age, body mass index (BMI), smoking, ethnicity, type of sport, concomitant injury to the medial or lateral collateral

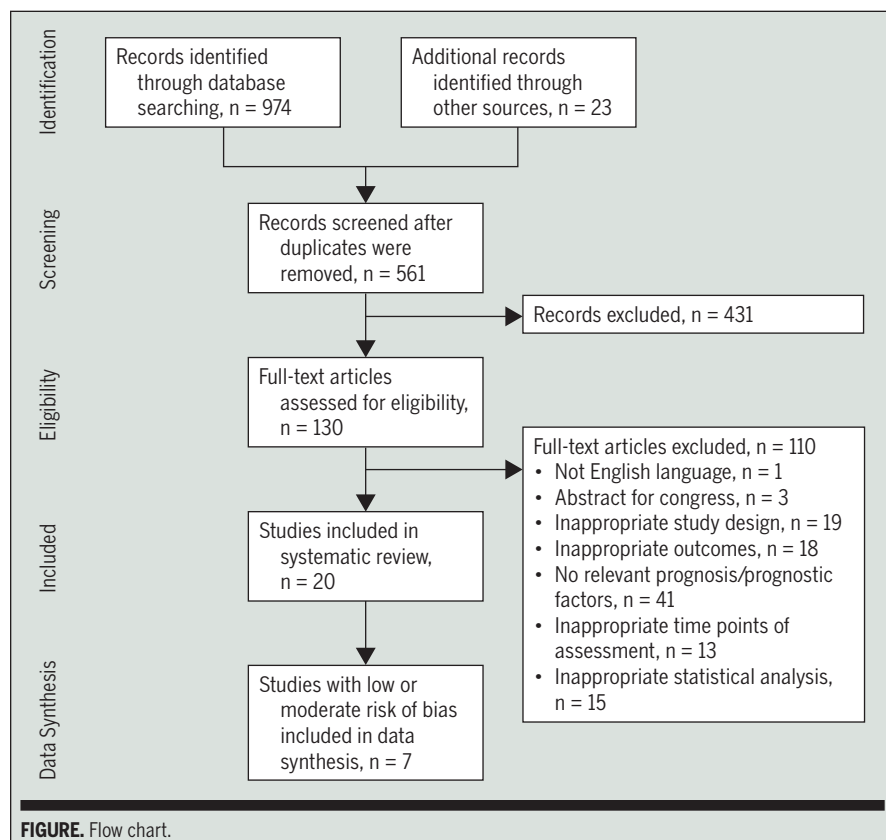


FIGURE. Flow chart.

TABLE 2

CHARACTERISTICS OF INCLUDED STUDIES (N = 20)

Study/Type	n	Treatment	Follow-up, y	Study Characteristics		Included in Data Synthesis	Patient Characteristics	
				Prognostic Factors Assessed	Outcome		Sex (female), %	Age, y ^a
Ageberg et al ¹ SKLR	10164	Primary ACLR	2	Age	KOOS	Yes	42	27
Barenius et al ⁸ SKLR	8584	Primary ACLR	2	Sex, age, baseline PROM, concomitant meniscus/cartilage injury, knee laxity, previous knee surgery	KOOS	No	49	NR
Brophy et al ⁹ MOON	2198	Primary or revision ACLR	2	Diabetes	IKDC-SKF KOOS Level of physical activity	No	44	24
Cox et al ¹⁴ MOON	1512	Primary or revision ACLR	6	Sex, age, BMI, smoking, education, ethnicity, type of sport, competition level, baseline PROMs, concomitant meniscus/cartilage injury	IKDC-SKF KOOS Level of physical activity	No	44	23
Dunn et al ¹⁷ MOON	446	Primary or revision ACLR	2	Sex, age, BMI, smoking, education, marital status, ethnicity, type of sport, competition level, baseline PROM, concomitant meniscus/cartilage injury, hearing a pop at injury	Level of physical activity	No	44	23
Ericsson et al ¹⁸ KANON	121	ACLR or nonsurgical	2 and 5	Early physical performance	KOOS	No	26	26
Filbay et al ²² KANON	121	ACLR or nonsurgical	5	Baseline PROM, concomitant meniscus/cartilage injury, knee extension deficit	KOOS	Yes	26	26
Hamrin Senorski et al ²⁷ SKLR	15204	Primary ACLR	2	Concomitant MCL/LCL or meniscus/cartilage injury	KOOS	Yes	50	NR
Ithurburn et al ⁴⁰ Cohort	48	Primary ACLR	2	Early physical performance	KOOS	No	77	18
Magnussen et al ⁴³ MOON	2333	Primary ACLR	2	Knee laxity	IKDC-SKF KOOS	No	44	27

Table continues on page 495.

ligament (MCL/LCL), meniscus, or cartilage, an audible pop at injury, knee laxity, extension range-of-motion deficit, and baseline PROMs. These factors were measured at baseline, preoperatively, or during ACL reconstruction.

Patient Characteristics One predictive study reported higher baseline BMI as a prognostic factor for worse 6-year IKDC-SKF and KOOS S/R outcomes, and smoking as a prognostic factor for worse IKDC-SKF score.⁶⁴ The same study found no association between higher BMI and KOOS QoL score, or between smoking and KOOS QoL and KOOS S/R scores.

There were no statistically significant associations between the factors of sex, age, ethnicity, and type of sport and the

outcomes of 2- and 6-year IKDC-SKF and KOOS scores.^{1,64}

Factors Related to the Injury Concomitant meniscus injury was reported as a prognostic factor in some studies, but not in others. Three studies (2 etiological and 1 predictive) of 3 different cohorts found a statistically significant negative association between concomitant meniscus injury and 2-year patient-reported success (KOOS-4 score in the 80th percentile or greater)²⁷ and 5- and 6-year KOOS S/R and QoL outcomes.^{22,64} The mean difference between those with and without concomitant meniscus injury was 10 to 14.4 points for the KOOS S/R^{22,64} and 8.9 points for the KOOS QoL.⁶⁴ The same studies found, however, no statistically significant associations between meniscus

injury and the other KOOS subscales and the IKDC-SKF.^{22,64} In 1 etiological study, concomitant meniscus injury was not a prognostic factor for any 2-year KOOS subscale.⁵⁹

Concomitant cartilage injury was assessed in 4 studies from 4 different cohorts.^{22,27,64,68} In 2 etiological studies, there was a statistically significant association between concomitant cartilage lesions and 5-year KOOS scores (all subscales), particularly for the full-thickness lesions.^{22,68} The mean difference between those with and without concomitant cartilage injury was 8.1 points for the KOOS S/R⁶⁸ and 8.0 to 12.3 points for the KOOS QoL.^{22,68} The results of Filbay et al²² applied only to the 5-year KOOS QoL score in patients with early (not delayed) ACL reconstruction.

TABLE 2

CHARACTERISTICS OF INCLUDED STUDIES (N = 20) (CONTINUED)

Study/Type	Study Characteristics					Patient Characteristics		
	n	Treatment	Follow-up, y	Prognostic Factors Assessed	Outcome	Included in Data Synthesis	Sex (female), %	Age, y ^a
Magnussen et al ⁴⁴ MOON	2333	Primary ACLR	6	Knee laxity	IKDC-SKF KOOS Level of physical activity	Yes	44	27
Nawasreh et al ⁵¹ Cohort	107	Primary ACLR	2	Sex, age, baseline PROM, early physical performance	Level of physical activity	No	34	27
Roessler et al ⁵⁶ KANON	121	ACLR or nonsurgical	2	Psychological factors	KOOS	No	26	26
Røtterud et al ⁵⁹ SKLR, NKLR	15783	Primary ACLR	2	Concomitant meniscus/cartilage injury	KOOS	Yes	42	26
Sasaki et al ⁶¹ RCT	150	Primary ACLR	2	Sex, age, BMI, baseline PROM, concomitant meniscus injury	KOOS	No	58	26
Sonnery-Cottet et al ⁶³ Cohort	541	Primary ACLR	3	Sex, age, type of sport, concomitant meniscus injury	Level of physical activity	No	27	22
Spindler et al ⁶⁵ MOON	314	Primary ACLR	5	Sex, age, type of sport, concomitant meniscus/cartilage injury, hearing a pop at injury, onset of swelling after injury	IKDC-SKF KOOS	No	45	27
Spindler et al ⁶⁴ MOON	448	Primary or revision ACLR	6	Sex, age, BMI, smoking, ethnicity, marital status, type of sport, baseline PROMs, concomitant MCL/LCL or meniscus/cartilage injury, hearing a pop at injury	IKDC-SKF KOOS Level of physical activity	Yes	43	23
Ulstein et al ⁶⁸ SKLR, NKLR	15783	Primary ACLR	5	Concomitant cartilage injury	KOOS	Yes	42	27
Wasserstein et al ⁷² MOON	1761	Primary ACLR	2 and 6	Sex, age, BMI, smoking, education, baseline PROM, concomitant meniscus/cartilage injury, previous knee pathology	KOOS	No	44	23

Abbreviations: ACLR, anterior cruciate ligament reconstruction; BMI, body mass index; IKDC-SKF, International Knee Documentation Committee Subjective Knee Evaluation Form; KANON, Knee Anterior Cruciate Ligament, Nonsurgical versus Surgical Treatment; KOOS, Knee injury and Osteoarthritis Outcome Score; LCL, lateral collateral ligament; MCL, medial collateral ligament; MOON, Multicenter Orthopaedic Outcomes Network; NKLR, Norwegian Knee Ligament Register; NR, not reported; PROM, patient-reported outcome measure; RCT, randomized clinical trial; SKLR, Swedish Knee Ligament Register.

^aValues are either median or mean.

In a third etiological study, the absence of concomitant cartilage injury predicted 2-year patient-reported success (as previously defined), while having a concomitant cartilage injury predicted failure (KOOS-4 score in the 20th percentile or less).²⁷ One predictive study found no association between concomitant cartilage injury and 6-year KOOS S/R and QoL and IKDC-SKF scores.⁶⁴

There were no statistically significant associations between concomitant MCL/LCL injury or an audible pop at injury and the outcomes of 2-year patient-reported success or failure²⁷ and 6-year IKDC-SKF, KOOS QoL, and KOOS S/R scores.⁶⁴

Knee Symptoms/Function In 1 etiological study, baseline KOOS-4 score predicted 5-year scores on the KOOS other symptoms, S/R, and QoL subscales, but not on the pain subscale, in patients with early ACL reconstruction.²² In those with delayed ACL reconstruction, baseline KOOS-4 score did not predict any of the 5-year KOOS subscale scores.²² A predictive study found conflicting results for the association between baseline and 5-year KOOS scores.⁶⁴

Preoperative knee laxity, defined as severely abnormal Lachman, anterior drawer, or pivot-shift test score, was assessed in 1 etiological study.⁴⁴ There was

a small, statistically significant association between preoperative knee laxity and 6-year IKDC-SKF and KOOS QoL scores (mean differences between those with and without preoperative laxity of 2.3 and 2.7 points, respectively) that was not considered clinically relevant.⁴⁴

There were no statistically significant associations between baseline Medical Outcomes Study 36-Item Short-Form Health Survey (SF-36) score and knee extension deficit greater than 10° and 5-year KOOS outcomes.²²

GRADE Evaluation for Prognostic Factors for PROMs in Patients Treated With ACL Reconstruction The evidence for con-

[LITERATURE REVIEW]

comitant meniscus and cartilage injuries was moderate certainty, while for the other factors it was low or very low certainty (TABLE 4). Our conclusions did not differ when all 20 eligible studies were included in the GRADE evaluation (supplemental material, available at www.jospt.org).

Prognostic Factors for Physical Activity in Patients Treated With ACL Reconstruction Prognostic factors for level of physical activity in patients treated with ACL reconstruction were assessed in 2 studies from the same cohort, both using the Marx Activity Rating Scale questionnaire as the outcome.^{44,64} The following 13 factors were assessed by 1 or more studies with moderate risk of bias: sex, age, BMI, smoking, marital status, ethnicity, type of preinjury sport, baseline PROMs, concomitant injury to the LCL/MCL, meniscus, or cartilage, knee laxity, and hearing a pop at injury (TABLE 2).

Patient Characteristics One predictive study assessed several demographic factors as possible prognostic factors

for 6-year Marx Activity Rating Scale score.⁶⁴ Female sex and worse baseline Marx Activity Rating Scale score were prognostic factors for worse 6-year Marx Activity Rating Scale score, while age, BMI, smoking, marital status, ethnicity, and type of preinjury sport were not.⁶⁴

Factors Related to the Injury None of the following factors were prognostic factors for 6-year Marx Activity Rating Scale score: concomitant MCL/LCL, meniscus, or cartilage injury and an audible pop at injury.⁶⁴ One etiological study found a statistically significant association between preoperative laxity (as previously defined) and 6-year Marx Activity Rating Scale score.⁴⁴ The mean difference between those with and without preoperative laxity was small (0.5 points) and not clinically relevant.⁴⁴

GRADE Evaluation for Prognostic Factors for Level of Physical Activity in Patients Treated With ACL Reconstruction Certainty of evidence was very low for all the prognostic factors for level of

physical activity in patients treated with ACL reconstruction. Serious limitations in several GRADE domains occurred because evidence for all factors was based on only 1 study with moderate risk of bias.

Prognostic Factors for PROMs and Physical Activity in Patients Treated With Rehabilitation Alone One etiological study separately assessed prognostic factors for 5-year KOOS-4 score in a group of patients treated with rehabilitation alone.²² None of the following factors were prognostic factors: baseline cartilage defect, meniscus damage, osteochondral lesion, extension deficit, SF-36 score, and KOOS-4 score.²² Certainty of evidence was very low due to few studies. No study assessed prognostic factors for physical activity in this patient group.

Differences in Prognostic Factors Between Treatment Groups One etiological study with low risk of bias assessed differences in prognostic factors between those treated with rehabilitation alone and with ACL reconstruction.²² Based on dif-

TABLE 3

RISK OF BIAS ASSESSMENT (N = 20)

	Study Participation	Study Attrition	Prognostic Factor Measurement	Outcome Measurement	Study Confounding	Statistical Analysis and Reporting	Overall
Ageberg et al ¹	Low	Moderate	Low	Low	Moderate	Low	Moderate
Barenius et al ⁸	Low	Moderate	Low	Moderate	Irrelevant	High	High
Brophy et al ⁹	Low	Low	Low	Low	High	High	High
Cox et al ¹⁴	Low	Low	Low	Low	High	High	High
Dunn et al ¹⁷	Low	Low	Low	Low	High	High	High
Ericsson et al ¹⁸	Low	Moderate	Moderate	Low	High	High	High
Filbay et al ²²	Low	Low	Low	Low	Low	Low	Low
Hamrin Senorski et al ²⁷	Low	Moderate	Moderate	Low	Low	Low	Moderate
Ithurburn et al ⁴⁰	Moderate	High	Low	Low	High	High	High
Magnussen et al ⁴³	Low	Low	Low	Low	Moderate	Moderate	Moderate
Magnussen et al ⁴⁴	Low	Low	Low	Low	Moderate	Moderate	Moderate
Nawasreh et al ⁵¹	Low	High	Low	Low	Irrelevant	Low	High
Roessler et al ⁵⁶	Low	Low	Low	Low	High	Moderate	High
Røtterud et al ⁵⁹	Low	Moderate	Low	Low	Low	Low	Moderate
Sasaki et al ⁶¹	Low	Low	Low	Low	High	High	High
Sonnery-Cottet et al ⁶³	Low	Low	Low	Low	High	High	High
Spindler et al ⁶⁵	Low	High	Low	Low	High	High	High
Spindler et al ⁶⁴	Low	Low	Low	Low	Irrelevant	Moderate	Moderate
Ulstain et al ⁶⁸	Low	Moderate	Low	Low	Moderate	Low	Moderate
Wasserstein et al ⁷²	Low	Low	Low	Low	Irrelevant	High	High

ferences in prognostic factors for 5-year KOOS-4 score between the treatment groups, the authors suggested that patients with concomitant meniscus injury and those with worse KOOS other symptoms, S/R, and QoL subscale scores in the early phase may benefit most from exercise therapy before choosing treatment.²²

DISCUSSION

CONCOMITANT MENISCUS AND CARTILAGE injuries were, with moderate certainty, prognostic factors for

worse PROMs 2 to 10 years after ACL reconstruction. Smoking, BMI, and baseline PROMs were prognostic factors for 2- to 10-year PROMs with very low certainty. For level of physical activity 2 to 10 years after ACL reconstruction, we concluded, with very low certainty, that female sex and worse baseline Marx Activity Rating Scale score were prognostic factors for worse long-term Marx Activity Rating Scale score. The other factors assessed in this systematic review were not associated with the outcomes. No studies included only patients treated with

rehabilitation alone. One study assessed differences in prognostic factors between patients treated with rehabilitation alone and those treated with ACL reconstruction.²² Patients with concomitant meniscus and cartilage injuries and lower KOOS scores in the acute phase may benefit most from an initial nonsurgical treatment choice, but further research on the topic is needed to draw conclusions. Hence, we could not answer the second aim of this systematic review.

The impact of the prognostic factors of BMI, smoking, baseline PROMs, sex,

TABLE 4

GRADE EVIDENCE PROFILE: POTENTIAL PROGNOSTIC FACTORS FOR 2- TO 10-YEAR PROMS IN ACL-RECONSTRUCTED PATIENTS FOR STUDIES WITH LOW OR MODERATE RISK OF BIAS (N = 7)

Potential Prognostic Factors	Studies, n	Patients, n	GRADE Factors ^a							Certainty
			1	2	3	4	5	6	7	
Sex ^b	1	448	× ^c	✓	✓	×	× ^d	×	×	Very low
Age ^e	2	10612	× ^f	✓	✓	×	× ^d	×	×	Low
Higher BMI ^g	1	448	× ^c	✓	✓	× ^c	× ^d	×	×	Very low
Smoking ^g	1	448	× ^c	× ^h	✓	×	× ^d	×	×	Very low
Ethnicity ^b	1	448	× ^c	✓	✓	×	× ^d	×	×	Very low
Type of sport ^b	1	448	× ^c	✓	✓	×	× ^d	×	×	Very low
Concomitant MCL or LCL injury ⁱ	2	15652	× ^f	✓	✓	×	× ^d	×	×	Low
Concomitant meniscus injury ^j	4	31556	✓	× ^h	✓	✓	× ^d	✓	×	Moderate
Concomitant cartilage injury ^k	4	31556	✓	× ^h	✓	✓	× ^d	✓	✓	Moderate
Hearing pop at injury ^b	1	448	× ^c	✓	✓	×	× ^d	×	×	Very low
Preoperative knee laxity ^b	1	2333	× ^c	✓	✓	×	× ^d	×	×	Very low
Preoperative extension deficit ^b	1	121	× ^l	✓	✓	×	× ^d	×	×	Very low
Higher baseline PROMs ^m	2	569	× ^f	× ^h	✓	×	× ^d	×	×	Very low

Abbreviations: ✓, no serious limitations; ×, serious limitations (or not present for moderate/large effect size, dose effect); ACL, anterior cruciate ligament; BMI, body mass index; GRADE, Grading of Recommendations Assessment, Development and Evaluation; LCL, lateral collateral ligament; MCL, medial collateral ligament; PROM, patient-reported outcome measure.

^aItems: 1, Study limitations; 2, Inconsistency; 3, Indirectness; 4, Imprecision; 5, Publication bias; 6, Moderate/large effect size; 7, Dose effect.

^bNonsignificant effect on multivariable analysis (1 study). The multivariable analysis represents a summary of the authors' conclusions when several outcomes for each factor were assessed.

^cEvidence is based on only 1 study with moderate risk of bias.

^dDue to a small number of included studies, we could not assess small-study biases with a funnel plot. We therefore cannot rule out publication bias.

^eNonsignificant effect on univariable analysis (1 study) and nonsignificant effect on multivariable analysis (1 study). The multivariable analysis represents a summary of the authors' conclusions when several outcomes for each factor were assessed.

^fEvidence is based on only 2 studies with moderate risk of bias.

^gNegative significant effect on multivariable analysis (1 study). The multivariable analysis represents a summary of the authors' conclusions when several outcomes for each factor were assessed.

^hInconsistency within/between study/studies.

ⁱNonsignificant effect on multivariable analysis (2 studies). The multivariable analysis represents a summary of the authors' conclusions when several outcomes for each factor were assessed.

^jNegative significant effect on multivariable analysis (3 studies) and nonsignificant effect on multivariable analysis (1 study). The multivariable analysis represents a summary of the authors' conclusions when several outcomes for each factor were assessed.

^kNegative significant effect on multivariable analysis (4 studies) and nonsignificant effect on multivariable analysis (1 study). The multivariable analysis represents a summary of the authors' conclusions when several outcomes for each factor were assessed.

^lEvidence is based on only 1 study with low risk of bias.

^mPositive significant effect on multivariable analysis (2 studies). The multivariable analysis represents a summary of the authors' conclusions when several outcomes for each factor were assessed.

and baseline Marx Activity Rating Scale score on outcomes was small (see supplemental material, available at www.jospt.org) and probably not clinically relevant. The impact of concomitant meniscus injury as a prognostic factor was larger, as the mean difference between those with and without meniscus injury was 10.0 to 14.4 points for the KOOS S/R^{22,64} and 8.9 points for the KOOS QoL.⁶⁴ The impact of concomitant meniscus injury on KOOS S/R outcomes, but not on KOOS QoL outcomes, was clinically relevant, with minimal important changes of 12.1 (95% confidence interval: 9.3, 14.8) points on the KOOS S/R and 18.3 (95% confidence interval: 16.0, 20.6) points on the KOOS QoL.³⁵ The impact of having a concomitant cartilage injury on the KOOS S/R (8.1 points) and QoL (8-12.3 points) outcomes also seemed important, but the mean differences between those with and without concomitant cartilage injury were below the minimal important changes for the instruments.^{22,68}

Comparison With Other Studies

The high methodological quality of this systematic review makes an important contribution to this field. Our high-quality search strategy, rigorous risk of bias assessment, and data synthesis ensured robust conclusions and recommendations for clinicians and patients. Due to these methodological factors, we could not replicate the findings of previous systematic reviews that male sex, younger age, and psychological factors were positive prognostic factors and that quadriceps weakness and range-of-motion deficits were negative factors.^{16,19}

To our knowledge, ours is the first systematic review to assess prognostic factors for PROMs and level of physical activity after ACL injury, both in patients treated with ACL reconstruction and rehabilitation alone. However, the paucity of studies on patients treated with rehabilitation alone made it impossible to answer questions regarding prognostic factors for PROMs and level of physical activity for this treatment group, or to

assess differences in prognostic factors between treatment groups.

Our results highlighted the importance of risk of bias assessments in systematic reviews, as 12 (60%) of the 20 included studies had high risk of bias. Bias was most often in the domains of “study confounding” and “statistical analysis and reporting.” Lack of clarity in aims and methods about whether studies were predictive or etiological was a recurring limitation. Effect estimates calculated from one model, often a prediction model, and presented in one table may mislead, because the underlying associations between covariates are not accounted for.⁷³ In many papers with an etiological aim but a statistically driven rather than a theoretically driven approach, it was unclear whether estimates were adjusted for all of the relevant confounders and should have been interpreted as total effect or direct effect.³² Epidemiological research methodology has developed over time, and the distinction between explanatory and predictive aims was less clear at the time when the included studies were performed.

Limitations

An important limitation in the literature in this field was the overlap of patients within the different publications from the MOON cohort and the Swedish and/or Norwegian Knee Ligament Registers. This overlap might have led to a correlation between study results that we could not account for. To minimize this problem, we included only the most recent publication of data from the same patients and on the same prognostic factors. Further, our strict inclusion criteria might have led us to miss high-quality research in which other PROMs than the IKDC-SKF, KOOS, and KOS-ADLS were used, such as the Lysholm Knee Scoring Scale, Anterior Cruciate Ligament-Return to Sport after Injury scale, and SF-36. The included studies did not differentiate between types of meniscus injuries, and we therefore could not assess prognosis after different injury types

(eg, dislocated bucket-handle tears versus stable, horizontal tears).

Our results apply to individuals with first-time, complete unilateral ACL injury, not including knee dislocations. The prognostic factors are also only applicable to the PROMs used in this study and to level of physical activity 2 or more and fewer than 10 years after ACL reconstruction. We did not consider psychological, overall health, or overall QoL outcomes.

Implications for Clinical Practice

When planning future physical activities and discussing patient expectations, it is useful for patients, physical therapists, orthopaedic surgeons, and athletic trainers to be aware that concomitant meniscus or cartilage injuries may lead to worse knee function 2 to 10 years after ACL reconstruction. As concomitant meniscus injuries are also the most frequently reported prognostic factor for knee OA after ACL injury,^{53,70} patients should be informed about preventive interventions for knee OA, such as knee extensor muscle strength training and maintaining a healthy body weight.^{20,28,41,54,57,74,75} Although with very low certainty, higher BMI was a prognostic factor for worse PROMs after ACL reconstruction. Due to the relationship of BMI to both knee function and development of knee OA, BMI should be incorporated as a prognostic factor in early patient education. We also found that smoking was a negative prognostic factor for PROMs. As this factor is modifiable, patients should be informed that avoiding smoking might contribute to better long-term outcomes.

Implications for Future Research on Prognostic Factors After ACL Injury and ACL Reconstruction

Future studies should be clear about whether their goals and methods are aimed at prediction or etiology. If the aim is etiological, authors should carefully state their hypothesis and background and run an informed causal analysis, ensuring that rules for adjustment for dif-

ferent types of covariates (confounders, mediators, and colliders) are followed.^{30,32} If the aim is predictive, authors should systematically build a prediction model based on all available predictors, study the model's discriminative ability and calibration, and, subsequently, internally and externally validate findings.^{11,66} Preregistration of study protocols for observational studies on prognostic factors might enable researchers to assess whether selective reporting and publication biases occur within this field.

Future high-quality prognosis studies should include patients treated with rehabilitation alone. This patient group is important, as it represents between 26% and 77% of the ACL-injured population.^{12,52,60} New studies should also compare prognostic factors between patients treated with rehabilitation alone and with ACL reconstruction in order to help clinicians identify those who have the best prognosis with ACL reconstruction and those who may succeed with rehabilitation alone. Future studies should also assess modifiable prognostic factors that can be targeted in early rehabilitation, such as muscle strength, range of motion, and hop performance.

Our systematic review also uncovered a lack of studies on level of physical activity in the long term after ACL injury. Most studies were at high risk of bias, and the study outcomes only included an activity rating scale (Marx Activity Rating Scale) and the prevalence of return to sport, neither of which aligns with the most common definition of level of physical activity,¹⁰ as they only measure participation in specific types of sports. Future studies should therefore include more general outcomes of level of physical activity (eg, accelerometry, International Physical Activity Questionnaire).

CONCLUSION

CONCOMITANT MENISCUS AND CARTILAGE injuries were prognostic factors for worse PROMs 2 to 10 years after ACL reconstruction. There was very

low-certainty evidence that higher BMI, smoking, and worse baseline PROMs were prognostic factors for worse PROMs, and that female sex and worse baseline Marx Activity Rating Scale score were prognostic factors for worse Marx Activity Rating Scale score 2 to 10 years after ACL reconstruction. ●

KEY POINTS

FINDINGS: We have moderate confidence that concomitant meniscus and cartilage injuries are prognostic factors for worse long-term patient-reported outcome measures after anterior cruciate ligament (ACL) reconstruction. The certainty is low or very low for other prognostic factors.

IMPLICATIONS: When planning future activities and discussing patient expectations, it is useful for patients, physical therapists, orthopaedic surgeons, and athletic trainers to consider that concomitant meniscus or cartilage injuries may lead to worse knee function 2 to 10 years after ACL reconstruction.

CAUTION: A large proportion (60%) of included studies in this systematic review were at high risk of bias, and there is a lack of studies on prognostic factors in patients treated with rehabilitation alone.

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors made a substantial contribution to the (1) conception/design of the study (Marie Pedersen and Drs Johnson, Grindem, Risberg, and Snyder-Mackler) or to the analysis or interpretation of the data (Marie Pedersen and Drs Johnson and Magnusson), and to the (2) drafting (Marie Pedersen and Dr Johnson) or critical revision (Drs Grindem, Magnusson, Risberg, and Snyder-Mackler) of the article. All authors gave final approval of the manuscript and agreed to be accountable for all aspects of the work.

DATA SHARING: All data relevant to the study are included in the article or are available as supplemental material (available at www.jospt.org).

PATIENT AND PUBLIC INVOLVEMENT: There was no patient or public involvement in this research.

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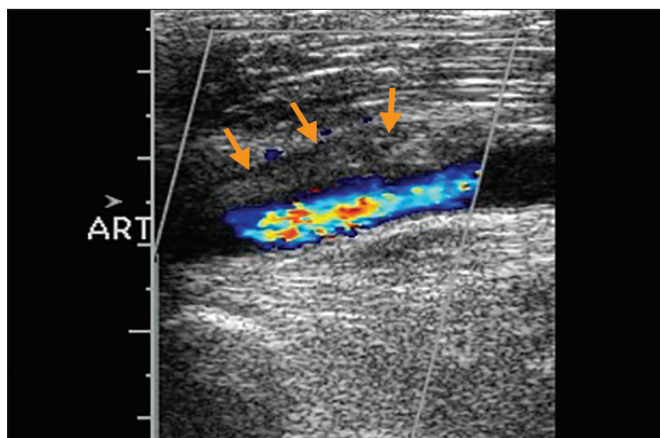


FIGURE 1. Left lower extremity long-axis-view ultrasound indicating aneurysmal dilation of the popliteal artery, with mural thrombus nearly contiguous with wall thickening (arrows).

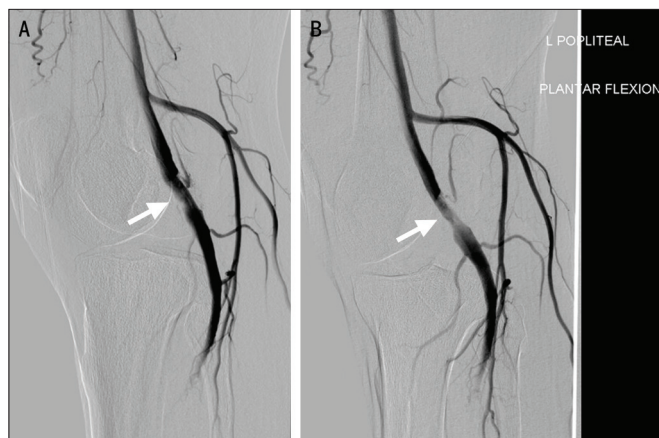


FIGURE 2. Digital subtraction angiogram of the left lower extremity at rest: (A) showing irregular contour of the left popliteal artery at rest due to thrombus and/or wall thickening (arrow) and with repeated ankle plantar flexion stress, (B) showing further narrowing of the left popliteal artery (arrow).

Popliteal Artery Entrapment Syndrome

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A 37-YEAR-OLD MILITARY SERVICE-member was referred to physical therapy with a greater-than-6-month history of low back pain with intermittent and worsening left posterolateral lower-leg pain and paresthesia with activity. He was diagnosed by his primary care physician with exertional compartment syndrome and referred to orthopaedic services. Chronic exertional compartment syndrome was ruled out via compartment pressure measurements. Subjective exam by the physical therapist revealed running-related posterolateral leg pain for several years that had evolved in the past 6 months to include calf cramping, which was now elicited within 5 minutes of exercise and resolved within 7 minutes of discontinuing physical activity.

Lumbar spine examination, including range of motion, slump, and straight leg raise testing, and posterior-to-anterior segmental mobility assessment did not provoke the patient's symptoms. The physical therapist noted a difference in distal lower extremity pulses and performed an ankle brachial index test, which produced an abnormal measure of 0.78.¹ This finding increased suspicion of popliteal artery entrapment and reduced the likelihood of lumbar spine pathology. The physical therapist ordered a duplex ultrasound, which demonstrated an anomaly at the popliteal artery (FIGURE 1), resulting in a diagnosis of popliteal artery entrapment syndrome, confirmed by computed tomography angiography and magnetic resonance imaging (FIGURE 2; FIGURES 3 through 5, available at www.jospt.org).³

The patient underwent popliteal artery bypass surgery (FIGURE 6, available at www.jospt.org), returned to full military duties within 4 months, and completed a marathon 10 months after surgery. Popliteal artery entrapment can be the result of aberrant anatomy or impingement by normal anatomic structures. Transient compression of the popliteal vasculature during provocation maneuvers (eg, plantar flexion) has been reported in 20% to 80% of asymptomatic individuals.^{2,3} The appropriate use of imaging modalities, coupled with thorough subjective examination and evidence-based physical examination tests, facilitated appropriate diagnosis and management for this patient. ● *J Orthop Sports Phys Ther* 2020;50(9):531. doi:10.2519/jospt.2020.9568

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Examination of Corticospinal and Spinal Reflexive Excitability During the Course of Postoperative Rehabilitation After Anterior Cruciate Ligament Reconstruction

Quadriceps femoris muscle weakness and voluntary activation failure can persist for years after anterior cruciate ligament reconstruction (ACLR).⁸ Deficits in quadriceps function are linked to altered biomechanics,^{5,13,18} worse self-reported function,^{6,12,19,24} and increased risk of reinjury.⁹ The underlying mechanism of quadriceps dysfunction is not completely understood. However, altered afferent information from the injured joint and the lack of afferent information from the native anterior cruciate ligament (ACL) may alter efferent drive to the muscle.²¹ Altered efferent drive to the quadriceps, manifested as strength deficits and/or

altered force control, may change knee loading during functional tasks and contribute to development of knee osteoarthritis.^{23,25,28} Direct measures of efferent drive (ie, corticospinal and spinal reflex-

ive excitability) are associated with quadriceps function 6 months after ACLR and later,^{15-17,26} yet there is a paucity of research examining these pathways prior to 6 months after ACLR.

Despite the increase in rate of ACLR among athletes,⁴ and the hypothesis that alterations in afferent and efferent pathways exist after ACLR, there is limited research on spinal reflexive and corticospinal excitability early after ACLR. The single study in the field found lower vastus medialis spinal reflexive excitability (Hoffmann reflex normalized to maximal M-wave) in patients 2 weeks after ACLR compared to matched controls, but no differences in corticospinal excitability.¹⁷ At 6 months after ACLR, patients with ACLR had lower corticospinal excitability (ie, higher motor thresholds) and no differences in spinal reflexive excitability compared to controls. These results suggest that changes occur in both the corticospinal and spinal reflexive pathways from 2 weeks to 6 months after ACLR. But it is unclear when this change occurs, and whether impairment resolution (ie, increased range of motion, decreased effusion, increased quadriceps strength) is associated with changes in corticospinal excitability.

● **OBJECTIVE:** To investigate corticospinal and spinal reflexive excitability and quadriceps strength in healthy athletes and athletes after anterior cruciate ligament reconstruction (ACLR) over the course of rehabilitation.

● **DESIGN:** Prospective cohort study.

● **METHODS:** Eighteen athletes with ACLR and 18 healthy athletes, matched by sex, age, and activity, were tested at (1) 2 weeks after surgery, (2) the "quiet knee" time point, defined as full range of motion and minimal effusion, and (3) return to running, defined as achieving a quadriceps index of 80% or greater. We measured (1) corticospinal excitability, using resting motor threshold (RMT) and motor-evoked potential amplitude at a stimulator intensity of 120% of RMT (MEP₁₂₀) to the vastus medialis, (2) spinal reflexive excitability, calculating the ratio of the maximal Hoffmann reflex

to the maximal M-wave to the vastus medialis, and (3) isometric quadriceps strength.

● **RESULTS:** The ACLR group had higher RMTs in the nonsurgical limb and higher MEP₁₂₀ in the surgical limb at all time points. The healthy-athlete group did not have interlimb differences. The RMT was positively associated with quadriceps strength 2 weeks after surgery; MEP₁₂₀ was associated with quadriceps strength at all time points.

● **CONCLUSION:** Compared to healthy athletes, athletes after ACLR had altered corticospinal excitability that did not change from 2 weeks after surgery to the time of return to running. *J Orthop Sports Phys Ther* 2020;50(9):516-522. Epub 1 Aug 2020. doi:10.2519/jospt.2020.9329

● **KEY WORDS:** anterior cruciate ligament reconstruction, corticospinal excitability, quadriceps

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Early rehabilitation after ACLR focuses on decreasing pain and effusion, restoring range of motion, and restoring quadriceps strength. Given that changes in pain, effusion, range of motion, and quadriceps function may affect the corticospinal and spinal reflexive pathways, we had 2 main objectives. The first objective was to measure spinal reflexive and corticospinal excitability to the vastus medialis at 3 time points during the course of rehabilitation in level 1 and 2 athletes¹¹ after ACLR and in healthy matched athletes. We hypothesized that spinal reflexive alterations would be present early after ACLR,¹⁷ and that corticospinal alterations would be present at the second and third time points in the ACLR group. We expected that the ACLR group would have less excitability (ie, higher resting motor thresholds [RMTs] and lower motor-evoked potential [MEP] amplitudes) compared to controls.¹⁷ The second objective was to assess the relationship between spinal reflexive and corticospinal excitability and quadriceps strength. We hypothesized that spinal reflexive excitability would be positively associated with quadriceps strength only at the 2-week time point, given that pain and effusion are present early after surgery, while corticospinal excitability would be positively associated with quadriceps strength at the second and third time points.

METHODS

Participants

EIGHTEEN ATHLETES (10 WOMEN, 8 men), 18 to 30 years of age, who had unilateral ACLR (9 hamstring autograft, 6 bone-patellar tendon-bone autograft, 3 allograft) were recruited for this cohort study from our institution's physical therapy clinic and community-based physical therapy clinics in the area. Nine different surgeons performed ACLR. Prior to injury, all athletes were participating in level 1 and 2 sports for at least 50 hours per year.¹¹ Rehabilitation for all athletes after ACLR followed a criterion-based protocol.¹

We recruited 18 uninjured athletes for this study by matching each participant in the ACLR group by sex and age to a level 1 or 2 athlete without a history of ACL injury or any other major lower extremity injury. Athletes were matched by competitive sport level. Six athletes in each group were Division I athletes, 2 were club-level collegiate athletes, 5 participated in intramural sports, and 5 in recreational sports.

Exclusion criteria for the patients were (1) multiple ligament reconstruction, (2) osteochondral procedures, (3) any previous lower extremity surgery, and (4) previous ACL injury. Metal or implants in the head or neck, and a history of neurological disease, seizures, severe migraines, and concussion within the last 6 months were transcranial magnetic stimulation (TMS)-specific exclusion criteria for both groups. This study was approved by the University of Delaware's Institutional Review Board, and written informed consent was obtained prior to enrollment. Athletes from this study were not involved in study design, interpretation, or translation of the research.

Paradigm

Testing was performed at 3 time points after ACLR: (1) 2 weeks after ACLR, (2) as soon as the athlete achieved a "quiet knee" (full range of motion, minimal or no effusion, and walking with no visible gait deviation), and (3) when the athlete was at least 12 weeks removed from surgery and had quadriceps strength of 80% or higher compared to the uninjured side. The third time point coincided with the start of the athletes' running progression and was therefore referred to as the return-to-running time point. The time between sessions for each athlete in the healthy group was determined by the time it took the matched athlete in the ACLR group to reach the second and third time points.

TMS Testing

Two measures of corticospinal excitability were obtained with single-pulsed TMS (Magstim BiStim² unit; The Magstim

Company Ltd, Whitland, UK). The first measure was RMT, which was defined as the lowest stimulator intensity required to elicit a measurable response (MEP of 50 μ V or greater) in at least 5 of 10 consecutive trials. The second measure was the peak-to-peak amplitude of MEPs elicited at an intensity of 120% of RMT and normalized to the peak-to-peak amplitude of maximal M-waves obtained during spinal reflexive testing (MEP₁₂₀). **APPENDIX A** (available at www.jospt.org) describes our TMS methods in more detail.

Spinal Reflexive Excitability

Athletes were positioned in supine, with a half-bolster under both knees, and electrical stimulation (DS7A high-voltage current stimulator; Digitimer Ltd, Welwyn Garden City, UK) was used to stimulate the femoral nerve. Intensity of the stimulation was slowly increased until the maximal Hoffmann reflex was produced. The stimulation was further increased to elicit the maximal M-wave. The Hoffmann reflex was normalized to the M-wave to create the H/M ratio used for data analysis.^{16,20} **APPENDIX A** describes our spinal reflexive methods in more detail.

Quadriceps Femoris Strength Testing

Athletes were seated in a Biodex dynamometer (Biodex Medical Systems, Inc, Shirley, NY), with the hips and knees flexed to 90° and 60°, respectively. Straps over the thigh and hips were secured tightly to prevent movement. Three warm-up trials (50%, 75%, and 100% of maximal effort) were performed to allow the participant to become familiar with the task. Following warm-ups, athletes performed 3 maximal voluntary isometric contractions, each lasting 5 seconds, with a 1-minute rest between each trial. The peak maximal voluntary isometric contraction from the 3 trials was recorded and normalized to body weight for analysis.

Statistical Analysis

G*Power software (Version 3.9.2; Heinrich-Heine Universität, Düsseldorf, Germany)⁷ was used to determine sample

size. Effect sizes of the primary outcome measure (RMT) were calculated based on pilot data. The power analysis indicated that a minimum of 16 athletes in each group were needed to demonstrate statistical significance of a between-group effect with an alpha level set at .05 and power of 0.80.

All statistical analyses were performed in SPSS Version 24 (IBM Corporation, Armonk, NY). Independent *t* tests were used to determine group differences in demographics. A 3-way mixed-model analysis of variance was used to investigate the main effects and interactions of group (ACLR versus healthy) by limb (surgical versus nonsurgical) by time point (2 weeks versus quiet knee versus return to running) for each neurophysiologic measure (RMT, MEP₁₂₀, and H/M ratio). Limb dominance determined the limb of each matched individual in the healthy group that was analyzed and compared with the surgical or nonsurgical limb of each individual in the ACLR group.²⁹ Post hoc *t* tests with Bonferroni corrections were performed when significant main effects or interactions were found. Effect sizes (Cohen's *d* with 95% confidence intervals) were calculated to quantify group differences for each measure at each time point. For the second objective, linear regression analysis was performed to determine the relationship between quadriceps strength of the surgical limb and RMT, MEP₁₂₀, and H/M ratio at each time point.

Secondary reliability analyses were performed for each neurophysiologic measure (APPENDIX B, available at www.jospt.org).

RESULTS

THE RMT WAS MEASURED IN ALL athletes. Three athletes in the ACLR group (2 men, 1 woman) had RMTs greater than 85% of maximal stimulator output in their nonsurgical limb, so MEP₁₂₀ could not be collected. We excluded those data from the MEP₁₂₀ analysis. Hoffmann reflexes were not elicited

for 1 participant (1 woman) with ACLR and 4 healthy athletes (1 man, 3 women), and we excluded their data from the H/M ratio analysis. Demographics and timing are listed in TABLE 1.

Objective 1 Results

There was a significant group-by-limb interaction for RMT ($P = .017$) (FIGURE 1) and MEP₁₂₀ ($P = .031$) (FIGURE 2). Athletes with ACLR had between-limb differences in RMT, with higher RMTs in the nonsurgical limb than in the surgical limb ($P = .011$). Healthy athletes had no limb-to-limb difference in RMT ($P = .398$). The nonsurgical limb had significantly higher RMTs (less excitability or more difficult to activate) than the healthy group's matched limb ($P = .004$). The RMT in the surgical limb was not different from that in the matched limb ($P = .097$).

Athletes with ACLR had between-limb differences in MEP₁₂₀, characterized by higher MEP₁₂₀ (greater excitability or more easily excited) in the surgical limb compared to the nonsurgical limb ($P = .012$). The healthy group did not display between-limb differences ($P = .661$). In the surgical limb, MEP₁₂₀ was significantly higher than in the matched limb of the healthy athlete group ($P < .001$). There were no differences in the nonsurgical limb compared to the matched limb of the healthy athlete group ($P = .137$). There were no main effects or interactions of time ($P \geq .587$), time by group ($P \geq .756$), or time by limb ($P \geq .442$), or

significant 3-way (group-by-limb-by-time) interactions ($P \geq .345$), for RMT or MEP₁₂₀. There were no significant main effects ($P \geq .384$) or interactions in regard to H/M ratio ($P \geq .172$) (FIGURE 3). Raw values (means and SDs) for all neurophysiologic measures are included in APPENDIX C (available at www.jospt.org).

Objective 2 Results

There was a significant positive association between surgical-limb quadriceps strength and RMT at 2 weeks ($P = .035$) (TABLE 2). There were significant negative associations between surgical-limb quadriceps strength and MEP₁₂₀ at all time points ($P \leq .016$). There were no significant associations between quadriceps strength and H/M ratio ($P \geq .225$).

DISCUSSION

WE AIMED TO INVESTIGATE CHANGES in the spinal reflexive and corticospinal excitability during rehabilitation after ACLR, and the relationships between these pathways and quadriceps strength. Our results suggest that corticospinal excitability in athletes with ACLR differed compared to that in healthy athletes early after surgery and during the course of rehabilitation. Corticospinal excitability was associated with quadriceps strength of the surgical limb throughout rehabilitation. These findings partially supported our hypotheses. First, spinal reflexive excitability al-

TABLE 1

PARTICIPANT DEMOGRAPHICS, TIMING OF TESTING SESSIONS, AND SELF-REPORTED FUNCTION^a

	ACLR Group	Control Group	P Value
Demographics			
Age, y	21.6 ± 3.3	22.3 ± 2.5	.495
Body mass index, kg/m ²	24.5 ± 3.0	23.4 ± 1.9	.188
Time from surgery to each time point, d			
2 weeks after ACLR	14.5 ± 2.2	...	...
Quiet knee	59.2 ± 19.4	...	...
Return to running	134.0 ± 36.5	...	...

Abbreviation: ACLR, anterior cruciate ligament reconstruction.

^aValues are mean ± SD unless otherwise indicated.

terations were not present at the 2-week time point, and alterations in corticospinal excitability were present at all 3 time points. Second, spinal reflexive excitability was not associated with quadriceps strength at any time point, and corticospinal excitability was associated with quadriceps strength at all 3 time points.

Surgical-Limb Alterations After ACLR

A key finding is that MEPs were elevated in the surgical limb of athletes after ACLR at all time points. We hypothesized that we would observe decreased excitability in the surgical limb. The MEP₁₂₀ measure provides a picture of the overall excitability of the cortical motoneuronal pool for a given muscle (here, the vastus medialis), or an indication of how easy or difficult it is to activate the motor cortex and descending pathway to the muscle.³⁰ We expected to see that the ability to activate the descending pathway was impaired, and that the degree of reduced activation would relate to the degree of quadriceps strength impairment. Instead, the ability of the cortex and corticospinal tract to activate the muscle was increased, suggesting that neuroplastic mechanisms were engaged early after ACLR. The fact that quadriceps strength was significantly negatively associated with MEP₁₂₀ amplitude was consistent with the idea that the weaker the muscle, the more the nervous system adapts by increasing excitability to activate the muscle. The fact that the relationship between quadriceps strength and MEP₁₂₀ was still present at the return-to-running time point may indicate that while quadriceps strength improved, alterations in excitability persisted.

We found a moderate effect size when comparing the surgical limb's RMT in athletes after ACLR to the control group's matched limb at all 3 time points: athletes with ACLR had somewhat higher RMTs, indicating less excitability. Higher MEP₁₂₀ (greater excitability) and higher RMT (less excitability) may seem contradictory and therefore deserve some discussion. The RMT reflects the intensity

of stimulation required to elicit muscle activation at the most minimal detectable level, whereas the MEP₁₂₀ reflects the magnitude of a muscle response when

the stimulator intensity is well above that required for minimal muscle activation.

Unlike MEPs, the RMT represents axon excitability via stimulation of the

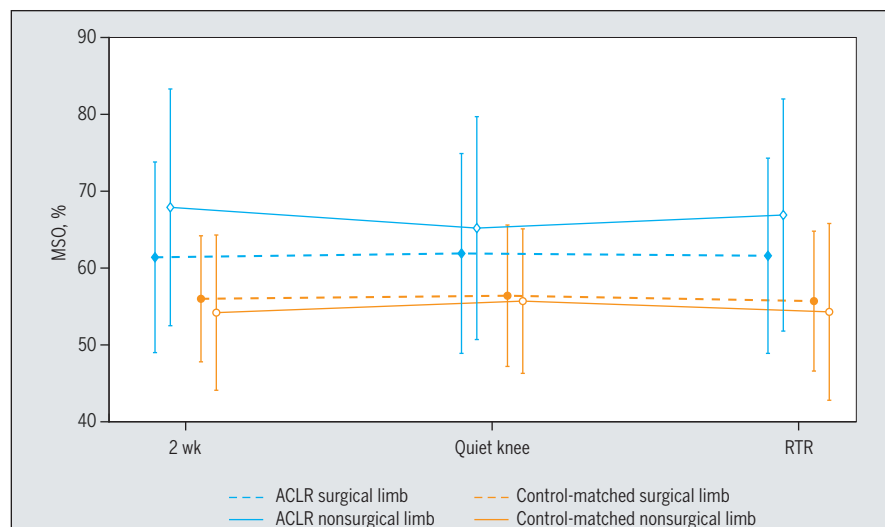


FIGURE 1. Resting motor thresholds in the ACLR group's (n = 18) surgical and nonsurgical limbs compared to the control group's (n = 18) matched limbs. Error bars represent mean $\pm$ 1 SD. Effect sizes (Cohen's *d* and 95% CI) quantified group differences (ACLR versus healthy control): surgical limb at 2 weeks: *d* = 0.55; 95% CI: -0.13, 1.20; quiet knee: *d* = 0.55; 95% CI: -0.13, 1.20; RTR: *d* = 0.53; 95% CI: -0.14, 1.19 and nonsurgical limb at 2 weeks: *d* = 1.07; 95% CI: 0.35, 1.74; quiet knee: *d* = 0.92; 95% CI: 0.22, 1.59; RTR: *d* = 0.94; 95% CI: 0.23, 1.60. Abbreviations: ACLR, anterior cruciate ligament reconstruction; CI, confidence interval; MSO, maximal stimulator output; RMT, resting motor threshold; RTR, return to running.

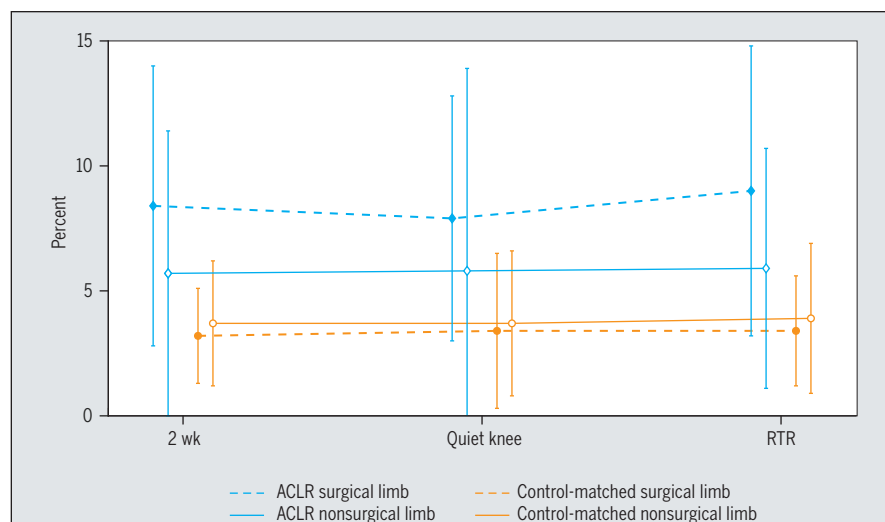


FIGURE 2. The MEP₁₂₀ in the ACLR group's (n = 15) surgical and nonsurgical limbs compared to the control group's (n = 18) matched limbs. Error bars represent mean $\pm$ 1 SD. Effect sizes (Cohen's *d* and 95% CI) quantified group differences (ACLR versus healthy control): surgical limb at 2 weeks: *d* = 1.18; 95% CI: 0.45, 1.86; quiet knee: *d* = 0.88; 95% CI: 0.18, 1.54; RTR: *d* = 1.20; 95% CI: 0.47, 1.88 and nonsurgical limb at 2 weeks: *d* = 0.47; 95% CI: -0.24, 1.15; quiet knee: *d* = 0.32; 95% CI: -0.36, 0.98; RTR: *d* = 0.44; 95% CI: -0.24, 1.10. Abbreviations: ACLR, anterior cruciate ligament reconstruction; CI, confidence interval; MEP₁₂₀, motor-evoked potential amplitude at an intensity of 120% of resting motor threshold, normalized to maximal M-wave; RTR, return to running.

[RESEARCH REPORT]

neurons directly synapsing with the corticospinal tract.³⁰ When stimulator intensities increase (eg, MEP₁₂₀), a more complex network of excitatory and inhibitory interneurons interacting on the

corticospinal tract is recruited.^{22,27,30} It is possible that multiple factors, including altered afferent signaling, pain, and fear after ACLR, may lead to an intrinsic decrease in axonal excitability of the excit-

atory axons of the corticospinal tract (ie, an elevated RMT). Neuroplastic mechanisms increasing overall excitation on the corticospinal tract (through the complex interaction of both excitatory and inhibitory interneurons) may occur in response to the elevated RMT to maintain efferent output to the quadriceps (ie, higher MEP₁₂₀).

Patients after ACLR have greater cortical activation, measured with functional magnetic resonance imaging, in the primary motor cortex contralateral to the surgical limb.¹⁰ Our finding of greater overall excitability (elevated MEP₁₂₀ measure) is consistent with this previous work and may reflect a greater number of neurons being recruited above the threshold, which could manifest as increased activation of the motor cortex with functional magnetic resonance imaging. Additionally, studies examining cortical activation with electroencephalography indicate that greater neurocognitive resources, especially in the frontal lobe of the cortex, are required by patients with ACLR when performing a force-matching or joint position sense task.^{2,3}

Higher MEP₁₂₀ and higher RMTs are partly in agreement with the only other longitudinal study examining corticospinal excitability after ACLR. Lepley et al¹⁷ found increased active motor thresholds to the vastus medialis bilaterally at 6 months after surgery compared to healthy controls. We found significantly higher RMTs to the nonsurgical limb, regardless of time point, and no significant differences in RMT to the surgical limb. Lepley et al¹⁷ also found no group differences in their MEP amplitude at 2 weeks or 6 months after ACLR. Differences in methodology (ie, active versus resting thresholds) may explain the discrepancy in findings. Another difference is that to determine time points we used functional status (based on impairments) rather than time alone. Controlling for time from surgery did not change our findings. Therefore, functional status may be as important as time from surgery when examining excitability after ACLR. Fu-

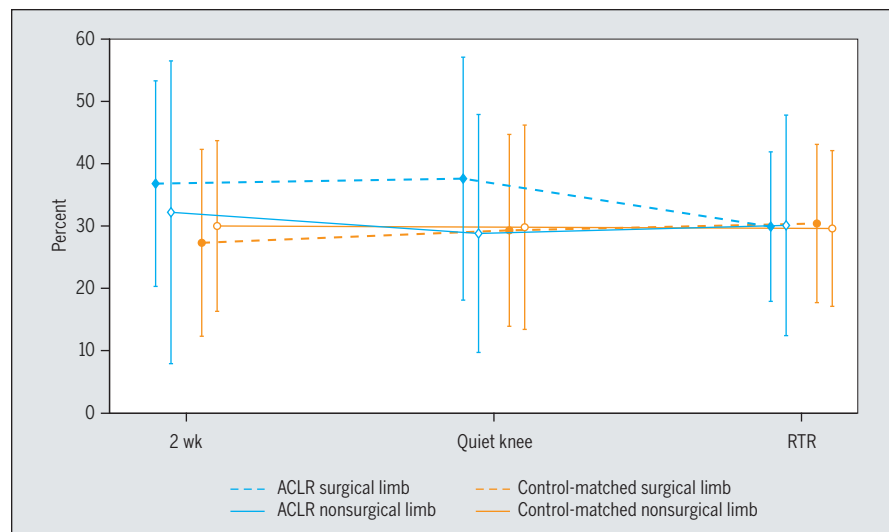


FIGURE 3. The H/M ratio in the ACLR group's (n = 17) surgical and nonsurgical limbs compared to the control group's (n = 14) matched limbs. Error bars represent mean $\pm$ 1 SD. Effect sizes (Cohen's *d* and 95% CI) quantified group differences (ACLR versus healthy control): surgical limb at 2 weeks: *d* = 0.60; 95% CI: -0.14, 1.31; quiet knee: *d* = 0.47; 95% CI: -0.26, 1.17; RTR: *d* = -0.041; 95% CI: -0.75, 0.67 and nonsurgical limb at 2 weeks: *d* = 0.11; 95% CI: -0.60, 0.82; quiet knee: *d* = -0.06; 95% CI: -0.76, 0.65; RTR: *d* = 0.03; 95% CI: -0.68, 0.74. Abbreviations: ACLR, anterior cruciate ligament reconstruction; CI, confidence interval; H/M ratio, Hoffmann reflex normalized to the maximal M-wave; RTR, return to running.

TABLE 2

LINEAR REGRESSION ANALYSES EXAMINING THE RELATIONSHIP BETWEEN QUADRICEPS STRENGTH AND EACH NEUROPHYSIOLOGIC MEASURE, BY TIME POINT, FOR THE ACLR GROUP

Time Point/Measure	R ²	β	P Value
2 wk after ACLR			
RMT	0.249	0.028	.035
MEP ₁₂₀	0.422	-8.481	.004
H/M ratio	0.096	1.346	.225
Quiet knee			
RMT	0.229	0.029	.052
MEP ₁₂₀	0.345	-9.041	.013
H/M ratio	0.000	0.045	.967
Return to running			
RMT	0.009	0.006	.711
MEP ₁₂₀	0.311	-7.764	.016
H/M ratio	0.024	-1.037	.556

Abbreviations: ACLR, anterior cruciate ligament reconstruction; H/M, Hoffmann reflex normalized to the maximal M-wave; MEP₁₂₀, motor-evoked potential amplitude at stimulator intensity of 120% of RMT; RMT, resting motor threshold.

ture research should consider using impairment- or function-based criteria for testing instead of time alone.

Nonsurgical-Limb Alterations After ACLR

Athletes with ACLR had significantly higher RMTs in the nonsurgical limb compared to the surgical limb and matched healthy limb. These findings suggest that bilateral alterations in corticospinal excitability were present after ACLR, yet the alterations were different between limbs. The higher RMTs in the nonsurgical limb could be due to a change in the intrinsic axonal excitability, similar to the surgical limb. However, there are likely different reasons for the higher RMT in the nonsurgical limb. Our results support previous research.¹⁰

Increased reliance on the nonsurgical limb and performance of extensive unilateral exercises may be factors contributing to lower activation in the motor cortex contralateral to the nonsurgical limb.¹⁰ Although it remains to be determined why there is an increased threshold for activation of the corticospinal pathway to the nonsurgical limb, it is clear that neuroplastic changes occur bilaterally after unilateral ACLR. Incorporating bilateral strengthening exercises and/or decreasing reliance on the nonsurgical limb early after ACLR may mitigate these potentially maladaptive alterations in cortical excitability/activation.

Clinical Implications

Current rehabilitation may not be sufficient for promoting appropriate and sustained brain changes capable of supporting safe return to high-level functional activities. Interventions known to induce neuroplastic brain changes, such as high-intensity, high-dose exercises, have potential to improve strength outcomes after ACLR.¹⁴ Additionally, interventions applied to the nonsurgical quadriceps muscle are warranted.

Limitations

We did not measure excitability prior to ACLR. We are therefore unable to deter-

mine whether the differences we found were due to the ACL injury or the surgery. We were unable to measure MEP₁₂₀ in the nonsurgical limb of 3 athletes within the ACLR group, yet group differences were still found. We could not elicit Hoffmann reflexes in 5 athletes, which may have affected our findings. We did not control for graft type.

CONCLUSION

ATHLETES AFTER ACLR HAD DISTINCT bilateral alterations in corticospinal excitability to the vastus medialis early after surgery, and these alterations did not change from 2 weeks after ACLR to the time of return to running. Alterations in corticospinal excitability were associated with quadriceps strength. ●

KEY POINTS

FINDINGS: Athletes with anterior cruciate ligament reconstruction (ACLR) had altered corticospinal excitability compared to matched controls, and corticospinal excitability was related to quadriceps strength.

IMPLICATIONS: Compensatory brain adaptations are likely a function of poor functional activation of the quadriceps muscle and may require consistent long-term follow-up to resolve.

CAUTION: Quadriceps dysfunction after ACLR is multifactorial. Future studies using multiple modalities to measure central nervous system activation and peripheral muscle changes are needed to fully understand quadriceps dysfunction after ACLR.

STUDY DETAILS

AUTHOR CONTRIBUTIONS: Dr Zarzycki was involved in all aspects of this study, including conception, data acquisition, data analysis, data interpretation, drafting the manuscript, and revisions. Drs Snyder-Mackler, Morton, Charalambous, Pietrosimone, and Williams were involved in conception, data analysis, data interpretation, drafting the manuscript,

and revisions. All authors confirmed the final version of this manuscript.

DATA SHARING: All data relevant to the study are included in the article or are available as online appendices.

PATIENT AND PUBLIC INVOLVEMENT: Athletes from this study were not involved in study design, interpretation, or translation of the research.

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APPENDIX A

FULL METHODS FOR NEUROPHYSIOLOGIC TESTING

Neurophysiologic Testing

After skin preparation, surface electromyography (EMG) electrodes (MA-300 EMG System; Motion Lab Systems, Inc, Baton Rouge, LA) were placed over the muscle bellies of the vastus medialis muscles bilaterally, based on published guidelines. Wraps were utilized to stabilize the electrodes and improve electrode-to-skin contact. Data were sampled at 5000 Hz and acquired using Signal Version 6.05 (Cambridge Electronic Design Ltd, Milton, UK). Electromyographic data were low-pass filtered at 2000 Hz online. Offline, the raw EMG signals were demeaned. This setup was used for both corticospinal excitability testing and spinal reflexive testing.

Transcranial Magnetic Stimulation Testing

During testing, participants were seated in a Biodex dynamometer (Biodex Medical Systems, Inc, Shirley, NY), with the hips and knees flexed to 60°. The vertex of the skull was identified as the intersection of a line marking the midpoint between the nasion and inion of the skull and a line marking the midpoint between the tragus of each ear.

Single monophasic transcranial magnetic stimulation (TMS) pulses (Magstim BiStim unit; The Magstim Company Ltd, Whitland, UK) delivered via a double-cone coil (outer wing diameter, 120 mm; maximum output, 1.4 T; intracranial current, posteroanterior) were utilized to obtain 2 measures of corticospinal excitability. The first measure was resting motor threshold (RMT), and the second measure was motor-evoked potential (MEP) amplitude at an intensity of 120% of RMT (MEP₁₂₀). Resting motor thresholds, rather than active motor thresholds, were examined in order to maximize TMS reliability. First, the "hot spot," which is the location on the head that elicited the greatest MEP to the contralateral vastus medialis, was identified using a suprathreshold intensity. All measurements were performed with the coil positioned manually at the hot spot, while markings drawn on the cap ensured consistent coil positioning throughout testing. The RMT was defined as the lowest stimulator intensity able to elicit a measurable response (MEP of 50 μ V or greater) in at least 5 of 10 pulses delivered with the limb at rest. The RMT is expressed as a percentage of the maximal stimulator output and reflects excitability of the central core region of a muscle's representation within the primary motor cortex. The MEP₁₂₀ was calculated as the average peak-to-peak amplitude of 10 MEPs produced by single pulses delivered at an intensity of 120% of RMT. Motor-evoked potential amplitudes for stimuli delivered at 120% to 130% of RMT (midrange of the stimulus-response curve) are commonly reported in the brain stimulation literature and considered representative of the overall excitability within the cortical motoneuronal pool. The MEP₁₂₀ values were normalized to the maximal M-wave values obtained during spinal reflexive testing, and were therefore not subject to biases that could be introduced by variations in electrode placement between participants or between sessions. During all TMS testing, pulses were delivered at a rate of less than 0.2 Hz to prevent conditioning of cortical excitability.

Spinal Reflexive Excitability

Participants were positioned in supine, with a half-bolster under both knees. A bar electrode from a DS7A high-voltage current stimulator (Digitimer Ltd, Welwyn Garden City, UK) was then positioned just lateral to the femoral artery over the femoral nerve. A 1-millisecond square-wave electrical pulse was delivered (at least 10 seconds between pulses) at varying intensities until a Hoffmann reflex was produced. The intensity of the stimulator was increased until the maximal Hoffmann reflex was produced, as reflected by a decrease in amplitude when testing at higher intensities. The intensity was then increased until a maximal M-wave was produced, as reflected by no further increase in amplitude with increased intensity of the electrical pulse. The average peak-to-peak amplitude of 3 maximal Hoffmann reflexes was normalized to the average peak-to-peak amplitude of 3 maximal M-waves to create the H/M ratio that was used for data analysis. During all reflex testing, stimuli were delivered at a rate of less than 0.1 Hz to prevent conditioning of the Hoffmann reflex.

APPENDIX B

SECONDARY RELIABILITY ANALYSIS

Methods

Ten additional healthy participants (4 men, 6 women; mean $\pm$ SD age, 23.6 ± 0.8 years; body mass index, 25.2 ± 3.4 kg/m²) were recruited to examine test-retest reliability of our corticospinal excitability (RMT and MEP₁₂₀) measures to determine whether the group differences found in this study exceeded measurement error. Both RMTs and MEP₁₂₀ were measured by the same examiner during 2 sessions held 24 to 48 hours apart. Sessions were held at the same time of day. Two-way random intraclass correlation coefficients (ICCs) for absolute agreement (ICC model 2,1) were calculated. Standard error of the measurement (SEM) was calculated for each measure by the following equation: $SEM = SD \times \sqrt{1 - ICC}$. Finally, the minimal detectable change (MDC) score was calculated using the following equation: $MDC = SEM \times 1.96 \times \sqrt{2}$. All ICCs were classified as excellent (0.75-1.00), good (0.60-0.74), fair (0.40-0.59), or poor (below 0.40).

Results

Both RMT and MEP₁₂₀ displayed excellent reliability (RMT: ICC = 0.966; 95% confidence interval: 0.913, 0.986; SEM, 0.36; MDC, 0.93% MSO and MEP₁₂₀: ICC = 0.899; 95% confidence interval: 0.765, 0.958; SEM, 0.003; MDC, 0.9% M-max).

Abbreviations: MEP₁₂₀, motor-evoked potential amplitude at an intensity of 120% of RMT; M-max, maximal M-wave; MSO, maximal stimulator output; RMT, resting motor threshold.

APPENDIX C

RAW DATA

Neurophysiologic Measures^a

Measure/Group/Limb	2 wk	Quiet Knee	RTR
RMT			
ACLR			
Surgical	61.4 ± 12.4	61.9 ± 13.0	61.6 ± 12.7
Nonsurgical	67.9 ± 15.4	65.2 ± 14.5	66.9 ± 15.1
Healthy control			
Matched surgical	56.0 ± 8.2	56.4 ± 9.2	55.7 ± 9.1
Matched nonsurgical	54.2 ± 10.1	55.7 ± 9.4	54.3 ± 11.5
MEP ₁₂₀			
ACLR			
Surgical	8.4 ± 5.6	7.9 ± 4.9	9.0 ± 5.8
Nonsurgical	5.7 ± 5.7	5.8 ± 8.1	5.9 ± 4.8
Healthy control			
Matched surgical	3.2 ± 1.9	3.4 ± 3.1	3.4 ± 2.2
Matched nonsurgical	3.7 ± 2.5	3.7 ± 2.9	3.9 ± 3.0
H/M ratio			
ACLR			
Surgical	36.8 ± 16.5	37.6 ± 19.5	29.9 ± 12.0
Nonsurgical	32.2 ± 24.3	28.8 ± 19.1	30.1 ± 17.7
Healthy control			
Matched surgical	27.3 ± 15.0	29.3 ± 15.4	30.4 ± 12.7
Matched nonsurgical	30.0 ± 13.7	29.8 ± 16.4	29.6 ± 12.5

Abbreviations: ACLR, anterior cruciate ligament reconstruction; H/M, Hoffmann reflex normalized to the maximal M-wave; MEP₁₂₀, motor-evoked potential amplitude at stimulator intensity of 120% of RMT; RMT, resting motor threshold; RTR, return to running.

^aValues are mean ± SD percent.