

Scoping Review

Anterior Cruciate Ligament Reconstruction Rehabilitation Utilizing Gait Metrics as Outcomes – A Scoping Review

Kyle Southall, PhD, LAT, ATC, PES, CSCS¹, Matthew P Ithurburn, PT, DPT, Ph.D.², C. Scott Bickel, Ph.D., PT³, Harshvardhan Singh, Ph.D.⁴, Megan Bell, M.S.⁵, Christopher P Hurt, Ph.D.^{1,6a}

¹ Program in Rehabilitation Science, University of Alabama at Birmingham, ² American Sports Medicine Institute, ³ Physical Therapy, Samford University, ⁴ Oklahoma State University, ⁵ University of Alabama at Birmingham, ⁶ Physical Therapy, University of Alabama at Birmingham

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Background

There is a growing body of knowledge linking common gait maladaptations seen in patients who have undergone an anterior cruciate ligament repair (ACLR) procedure and early-onset OA of the knee. These maladaptations present during the early stages of recovery following ACLR and often persist up to five to seven years, and likely beyond, after surgery.

Purpose

The purpose of this scoping review was to investigate the literature on therapeutic interventions after ACLR whose purpose is to normalize gait biomechanics.

Study Design

Scoping Review.

Methods

PubMed, SPORTDiscus, CINAHL, Embase, and Scopus databases were searched using predefined terms such as Anterior Cruciate Ligament, Gait, Locomotion. Two authors independently reviewed abstracts and full texts. Inclusion criteria included: 1) articles published between 1990 and 2023, 2) written in English, 3) conducted using human participants, 4) full text available, 5) included participants who were between the ages of 18-35 years and had undergone an ACLR procedure within five years of the relevant intervention, and 6) included outcomes measures focused on walking/gait metrics after receiving a therapeutic intervention. Exclusion criteria were Case studies, case series, and studies using non-living subjects, such as animal studies or human cadaver studies.

Results

Of the 2873 potential studies 14 studies including 404 participants met all criteria. Six studies included targeted strengthening as an adjunct to a normal ACLR rehabilitation protocol, two included partial bodyweight training via treadmill, three included assistive devices for gait or real time feedback via assistive devices, two included vibration therapy, and one included a harmonic oscillator intervention. The high variability of interventions on a limited number of participants makes it difficult to generalize their applicability in the clinical setting on a large scale. Especially as few studies have evaluated the effects of interventions specifically on gait metrics.

^a Corresponding Author:
Christopher P Hurt
1716 9th Avenue South,
Birmingham, AL 35233
Fax: 1-205-975-7787
Telephone: 1-205-934-8517
cphurt@uab.edu

Conclusion

There is a noted lack of standardization of prospective interventions to normalize gait after ACLR that also includes a long-term follow-up. These interventions are important to potentially help preserve long-term knee health in individuals with ACLR. There is a present need for rigorous therapeutic intervention that addresses common gait maladaptations after ACLR to potentially help preserve the long-term knee health in individuals with ACLR.

Level of Evidence

2

INTRODUCTION

Approximately 200,000 anterior cruciate ligament (ACL) injuries occur annually in the United States to patients commonly in their mid-teens to early 20s. The primary treatment for these individuals is ACL reconstruction (ACLR).¹⁻³ It is well-documented that individuals after ACLR are at increased risk to develop long term knee problems, such as early-onset osteoarthritis (OA) of the knee, with the reported prevalence ranging from 40% to 85% of patients 10-15 years after surgical intervention.⁴⁻⁸ Early-onset knee OA in those following ACLR is associated with significant pain, decreased quality of life (QoL), financial strain, and a significant burden on the healthcare system.^{9,10} The incidence of knee OA in persons following ACLR is much higher than the general population, where knee OA prevalence rates are reported from 20-24%,^{11,12} and typically much later in life. Thus, understanding the extent that early-onset OA of the knee is attributable to modifiable mechanisms after ACLR represents a significant clinical problem and intervention target for researchers and clinicians.

There is a growing body of knowledge linking common gait maladaptations seen in patients who have undergone an ACLR procedure and early-onset OA of the knee.¹³⁻¹⁶ Gait maladaptations, such as decreased knee range of motion (ROM), increased sagittal plane knee flexion angle at initial contact, decreased knee extension moment, and decreased vertical ground reaction force (vGRF) early in stance present following ACLR^{15,17} and often persist at least five to seven years after surgery and likely beyond.¹⁸ In the frontal plane, an increased knee adduction moment resulting in varus positioning is a common finding in this population.^{13,19-22} This has led to emerging theories that the etiology of early onset of osteoarthritis may relate to an altered loading environment at the knee created by gait maladaptations.²³⁻²⁶ Because individuals after ACLR are active, even slight alterations to the loads that are experienced by the articular surfaces of the distal femur and proximal tibia and the remaining meniscus, when compounded over the course of millions of steps, may have detrimental long-term effects on knee joint health. Thus, therapeutic interventions that directly address gait maladaptations are of critical importance in the clinical setting after ACLR.

The purpose of this scoping review was to investigate the literature on therapeutic interventions after ACLR whose purpose is to normalize gait biomechanics. By identifying interventions and normalization of gait outcomes, we hope to encourage further study that leads to future implemen-

tation of effective interventions to mitigate the risk of early-onset OA of the knee, improving the long-term knee health of ACLR patients.

METHODS

IDENTIFYING THE RESEARCH QUESTION

Due to the large number of gait studies on therapeutic interventions post ACLR the search aimed to be as broad as possible using an a priori review protocol shared between co-authors (KS, SB, MI). The research question was: what therapeutic interventions are present in the literature that affect walking gait post ACLR?

ELIGIBILITY CRITERIA FOR STUDIES

To be included in the analysis each study must have: 1) been published between 1990 and 2023, 2) written in English, 3) conducted using human participants, 4) full text available, 5) included participants who were between the ages of 18-35 years that had undergone an ACLR procedure within five years of the relevant intervention, and 6) included outcomes measures focused on walking/gait metrics after receiving a therapeutic intervention. Exclusion criteria included, case studies, case series, wrong comparator (i.e., using gait as a training intervention but not assessing gait outcomes) and wrong setting such animal studies or human cadaver studies.

INFORMATION SOURCES AND SEARCH PROCEDURES

Search terms were identified to address the purpose of the study and used to develop search strategies for six databases including PubMed, SPORTDiscus, CINAHL, Scopus, CENTRAL, Embase, (see Appendix). Main search terms centered around anterior cruciate ligament reconstruction, gait, and outcomes. Data extraction was completed in 2023 to yield a comprehensive search of existing literature related to the topic. The search (MB) and evaluation of search results were performed according to Joanna Briggs Institute (JBI) Reviewers Manual for Developing a scoping Review.^{27, 28}

STUDY SELECTION

The identified studies from the database searches were compiled into a single EndNote library and uploaded to an

online systematic review program, Covidence (Melbourne, Australia). Once uploaded, duplicate studies were removed. Two independent reviewers (KS and MI) screened titles, abstracts, full texts using Covidence (Melbourne, Australia) based on inclusion and exclusion criteria. If a conflict was identified between the two initial reviewers, a third reviewer (SB) cast the final vote.

CHARTING THE DATA

Upon compilation of the list of included articles, the evaluation of the interventions and findings to evaluate pertinent dichotomies began. It was found that many used similar intervention lengths; single session, less than 12 weeks, and greater than 12 weeks. This offered a feasible means of compiling the data in chart form for a succinct report of findings.

CRITICAL APPRAISAL

In this scoping review, the aim was to report on the breadth of the available published evidence regarding therapeutic interventions that affect gait after ACLR. As critical appraisals are not required by scoping reviews, an in-depth critical appraisal was not performed.²⁹ This approach has been accepted and supported by the database of scoping reviews on health-related topics,^{27,30} especially in those reviews where scarce findings do not facilitate systematic review or meta-analysis.^{27,28}

SYNTHESIS OF THE RESULTS

The final stage of the scoping review process as described by Arksey and O'Malley²⁹ is a thematic analysis to enable the investigation of the included studies in depth to produce a thorough summary. In this thematic analysis, interventions fell into three categories: durations consisting of a single session, less than 12 weeks, or greater than 12 weeks. There was a wide array of therapeutic interventions utilized and subsequent gait evaluation metrics. This added to the complexity of the topic and highlights the critical need for further therapeutic interventions to address gait maladaptations post ACLR that are well studied and readily available in clinical settings.

RESULTS

Utilizing common search terms and subsequent MeSH terms found in the Appendix, a total of 2873 articles were assessed for suitability for inclusion in this scoping review (Figure 1).

A total of 14 studies including 404 total participants (Table 1) met the eligibility requirements, with the earliest publication being from 2004 and the most recent from 2021.

Of the 14 publications, three included a single laboratory visit³¹⁻³⁴ while 11 were prospective intervention studies³⁵⁻⁴⁴ (Tables 1 and 2). Of these analyzed studies, six included targeted strengthening in addition to a normal ACLR rehabilitation protocol, two included partial body-

weight gait training via a specialized treadmill, three included assistive devices used during gait or real time feedback via assistive devices, two included vibration therapy, and one included a harmonic oscillator intervention (Table 2). Among the prospective studies, the length of the interventions ranged from four weeks to six months, and the frequency of the interventions ranged from one training session per week to five days a week (Table 1). Follow-up periods were generally short for all studies (<six months), however there were three studies that provided two-year follow-up data.^{35,36,38} Four of the 11 prospective intervention studies resulted in a positive change in knee range of motion and/or knee joint kinetics.^{37,39,42,44} Of interest, only one of the four studies used walking as the training modality,³⁹ while the other studies focused on neuromuscular training,⁴⁰ knee extensor eccentric training³⁷ or core stabilization⁴⁵ (Table 2). We observed a variety of outcome measures utilized in these studies (Table 2). They ranged from "low tech" clinical tests (TUG, 10-m walk) to more high-tech instrumented tests (3D motion capture, EMG).

DISCUSSION

The purpose of this review was to perform a scoping review to investigate various therapeutic interventions after ACLR to specifically normalize gait biomechanics. Fourteen studies that satisfied the inclusion and exclusion criteria were included. Those investigations used a range of interventions. The mechanics of walking, given its central role in performing activities of daily living, likely plays a key role in an individual's long term knee health and the reported altered loading cycles that occur each step for those with ACLR have been hypothesized to contribute to EOA.^{46,47} While this provides a motivation to identify modifiable risk factors to reduce risk of EOA, there are a limited number of evidence-based therapeutic interventions that specifically address known gait maladaptations after ACLR.

Alterations in gait can change the loading environment, with potential ramifications on the articular surface of femur and tibia, as well as the meniscus. This has led to a hypothesis that gait maladaptations alter the loading of knee cartilage after ACLR creating conditions for both overloading^{13,48-51} and/or underloading^{19,46,47,49} of the cartilage within the knee. Andriacchi et al. described the onset of OA occurring as a combination of two proposed theories. One theory proposes that individuals who adopt a high functional loading response on the knee joint develop rapid progression of OA. A second theory suggests that individuals who adapt to a low functional loading develop a slower progression of OA due to under loading.⁴⁸ Another crucial component to this theory is that cartilage thickness is attributed to both joint loading and the number of loading cycles.^{13,52} This can be interpreted as a potential finite balance between sufficient loading cycles to encourage cartilage hypertrophy and too much loading and/or alterations in how the cartilage is loaded resulting in premature breakdown.⁴⁹ This emphasizes the importance of normalizing gait as efficiently as possible as walking is the dominant cyclic activity of daily living.^{5,13,19,20,49}

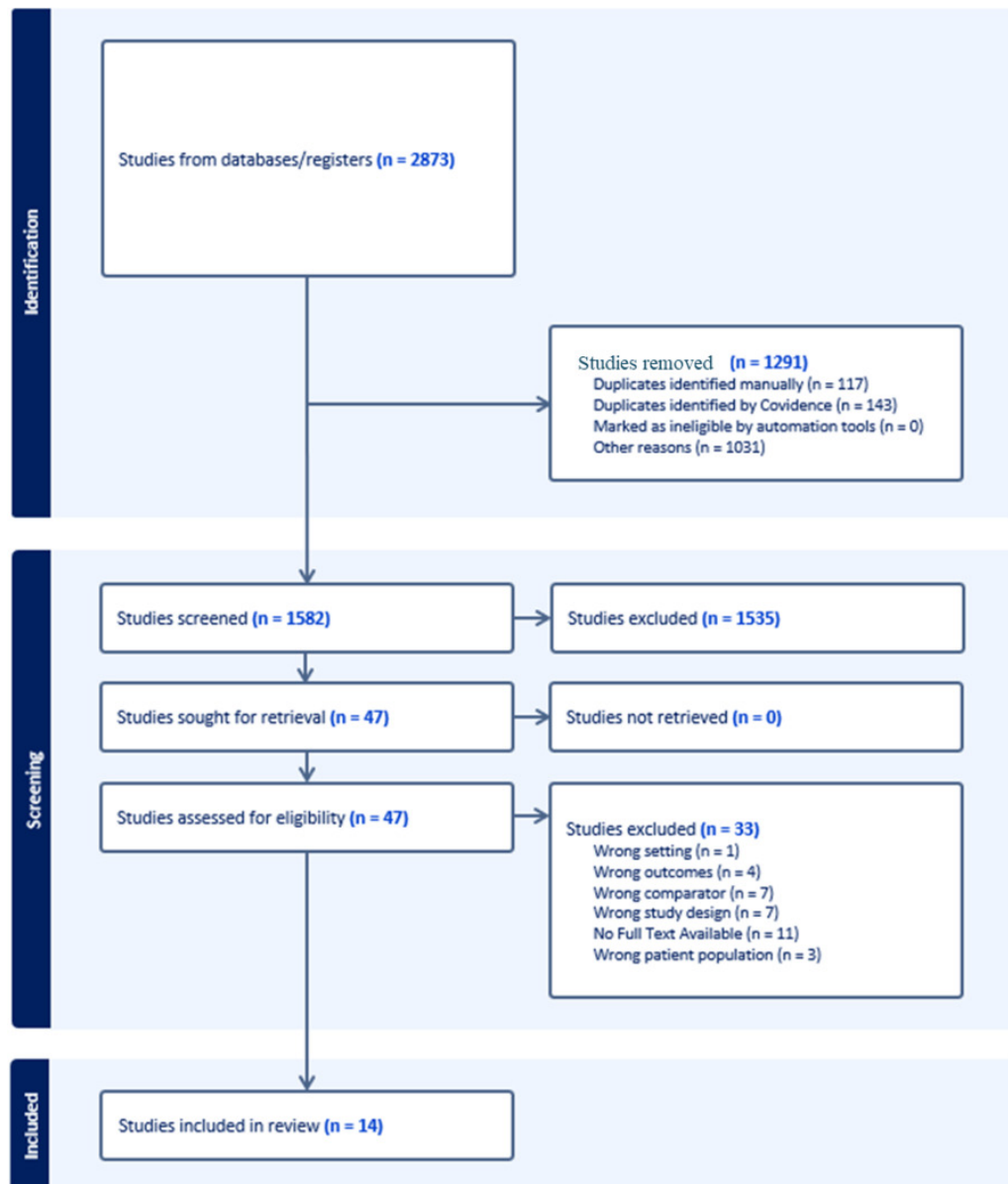


Figure 1. PRISMA Flow Diagram for scoping review process.

While multiple studies were identified that were able to demonstrate normalization of key features of gait at varying levels of evidence, they used a variety of interventions on a very limited number of subjects making it difficult to generalize their applicability in the clinical setting on a large scale. This identifies a need for a scalable intervention to mitigate gait maladaptations after ACLR that is feasible to apply in the clinical setting. While clinicians have shown a recognition that gait interventions after ACLR are important⁵³ the findings of this scoping review suggest that relatively few studies exist attempting to normalize and/or assess gait after ACLR. Reducing gait maladaptations such as decreased knee range of motion (ROM), decreased knee flexion angle at initial contact in the sagittal plane and a decreased knee extension moment, and increased vertical ground reaction force (vGRF) during loading^{21,52,54-58} after ACLR are modifiable factors that may affect the onset of early-onset knee OA in individuals with ACLR.

While the modifiable nature of post ACLR interventions provides promise, recent work shows that while many clinicians ascribe value to gait training during rehabilitation, only 35% of respondents reported objectively measuring gait during rehabilitation.⁵³ Furthermore, given the findings of this review, there are very few well studied therapeutic interventions that mitigate gait maladaptations after ACLR. Given the subtle nature of gait maladaptations, the use of sensitive means of quantifying pre-post changes to gait are important.^{59,60} The recent advent of valid and reliable means to quantify aspects of gait using 2D based camera technology,^{61,62} markerless multiple camera views to reconstruct 3-dimensional video capture outside the lab,^{61,63} or wearable technology⁶⁴⁻⁶⁶ is providing clinicians and scientists means to perform these quantitative assessments in clinical settings.

Many of the included studies demonstrated significant variation in the type and focus of the therapeutic inter-

Table 1. Intervention Study Characteristics

Single Session Interventions			
Author	Study Design	Participants	Length of Intervention
Blackburn et al. 2021 ³¹	RCT	50 ACLR participants avg. 20 yrs. old 26.7 months after surgery	Single testing session
Hu et al. 2016 ³²	Single-arm Prospective Study	10 ACLR participants avg. 33 yrs. old immediately after surgery	Single testing session
Hunt et al. 2010 ³³	Pre-post Single Session Intervention	12 ACLR participants avg. 21 yrs. old 1 month after surgery	Single testing session
Interventions of Less Than or Equal to 12 Weeks			
Luc-Harkey et al. 2018 ³⁴	Crossover Design Study	30 ACLR participants avg. 20 yrs. old 4 years after surgery	One month
Capin, et al. 2019 ³⁵	RCT	39 female ACL participants avg. 19 yrs. old 5.5 months after surgery	Five weeks
Capin et al. 2018 ³⁶	RCT	40 ACL participants avg. 23 yrs. old 5.5 months after surgery	Five weeks
Coury et al. 2006 ³⁷	Prospective non-randomized study	5 male ACL participants avg. 32 yrs. old 9 months after surgery	Twelve weeks
Capin et al. 2017 ³⁸	RCT	40 ACLR participants avg. 23 yrs. old 5.5 months after surgery	Five weeks
Decker et al. 2004 ³⁹	RCT	16 ACLR participants avg. 28 yrs. old 6 weeks after surgery	Six weeks
Moran et al. 2019 ⁴⁰	RCT	23 ACLR participants avg. 21 yrs. old 1 week after surgery	4 weeks.
Luo et al. 2016 ⁴¹	RCT	40 ACLR participants avg. 43 yrs. old Immediately after surgery	24 weeks
Hartigan et al. 2009 ⁴²	RCT	19 ACLR participants avg. 29 yrs. old Pre-surgery	3 weeks prior to ACLR
Eastlack et al. 2005 ⁴³	Prospective non-randomized study	6 ACLR participants avg. age 41yrs. old 6 weeks after surgery	6 weeks
Interventions of Greater Than 12 Weeks			
Li et al. 2019 ⁴⁴	RCT	74 ACLR participants avg. 27 yrs. old 2 nd day after surgery	6 months

Randomized controlled trial =RCT, Anterior Collateral Ligament Reconstruction = ACLR, avg.=average, yrs.=years

ventions used to address altered gait, including focus on proprioception, eccentric strengthening, core stability, biofeedback, partial body-weight training, and joint mobilizations. To add to the difficulty of applying these interventions clinically, the studies highlighted were observed to include low standardization of timing, volumes, intervention types, and gait metrics as outcome measures. For this scoping review the authors appraised investigations that were single session studies (n=3) and prospective interventions (n=11). The single session investigations tested the effectiveness of acute interventions such as local muscle and whole-body vibration,³¹ robotic intervention,³² biofeedback while walking³⁴ and anterior tibiofemoral glides.³³ Each of these acute interventions led to improvements in the specific kinetic or kinematic gait outcomes with one study showing that gait modifications were still present one month post-intervention.³² It is not clear to the extent that these unique interventions would result in long term or sustained effects on knee joint kinetic and kinematics due to their single visit, cross sectional design. Some of the prospective interventions assessed showed

promise at normalizing gait metrics, however the long-term efficacy of these treatments is unknown. Two investigations that reported positive findings showed promising long-term results at six months post ACLR.^{42,45} The short-term nature of the interventions (nine of the ten interventions lasted 12 weeks or less with limited follow-up) do not allow the assessment of implications on gait along a longer time horizon, especially pertaining to long term functional gait, as the outcome metrics were also highly variable. Of note, three investigations did assess outcomes at one- and two-year post-op. These studies failed to show meaningful improvement in these outcomes related to alterations in function of the reconstructed knee.^{35,36,38} These authors suggested that longer interventions may be required. Further studies standardizing interventions and evaluating the gait metric outcomes are needed before adopted into clinical practice, especially as many of these interventions are not commonly being utilized in clinical practice.⁵³

Table 2. Intervention Studies with Gait Metrics as Outcomes.

Single Session Interventions			
Author	Intervention	Gait Metric	Notable Outcomes
Blackburn et al. 2021 ³¹	Participants randomized to local muscle vibration (LMV) at the quadriceps vs whole body vibration (WBV) assessed pre-post	3D motion capture and kinetics to assess peak vertical ground reaction forces (vGRF) and its loading rate, peak internal knee extension and abduction moments (KEM), and peak knee flexion and varus angles.	WBV acutely increased peak KEM and LMV decreased loading rates compared to controls.
Hu et al. 2016 ³²	Participants completed regular walking and robotic assisted therapy for a single session of 20 minutes. Outcomes assessed pre-post.	10 min walk test and timed-up-and-go test. Surface Electromyography (sEMG) of the vastus medialis (VM) during the gait cycle.	Times for both the 10MWT and TUG test decreased significantly. VM sEMG activity increased. A follow-up study confirmed these findings to be persistent at one-month post-intervention
Hunt et al. 2010 ³³	Participants experienced anterior tibiofemoral glides performed for 10 minutes. Outcomes assessed pre, post, and 10 minutes following the intervention.	3D motion capture gait analysis via Eagle Cameras, Motional Analysis Corp).	Maximum knee extension increased acutely during stance phase of gait acutely but did not last at follow up. No other gait metric showed a significant difference post intervention.
Interventions of Less Than or Equal to 12 Weeks			
Luc-Harkey et al. 2018 ³⁴	Participants completed 4 separate walking trials while receiving real-time biofeedback of vertical ground reaction force (vGRF) projected on a screen at a self-selected walking speed for 20 minutes. Outcomes assessed during the session.	3D motion capture gait analysis and force plate metrics during gait cycle.	Peak vGRF of the ACLR limb increased significantly during high loading and decreased during low loading compared to control indicating a cueing an increase in vGRF may be beneficial for increasing knee extension moment, and knee excursion in ACLR patients.
Capin, et al. 2019 ³⁵	Participants randomized into a 10-session strength, agility, plyometric, and secondary prevention (SAPP) training or SAPP training plus perturbation training. Outcomes assessed pre-post-1yr 2yr follow up.	Limb symmetry during walking via 3D motion capture, force plates, and EMG.	Neither SAPP nor SAPP + PERT training improved walking mechanics in women at up to 2 years post-op.
Capin et al. 2018 ³⁶	Participants randomized to a 10-session strength, agility, plyometric, and secondary prevention (SAPP) training or a SAPP training plus perturbation training. Outcomes assessed pre-post-1yr 2yr follow up.	Limb symmetry during walking via 3D motion capture, force plates, and EMG.	Neither SAPP nor SAPP + PERT training improved walking mechanics in men at up to 2 years post ACLR.
Coury et al. 2006 ³⁷	Participants performed 3 sets of 10 maximal eccentric quadricep contractions twice a week for 12 weeks. Outcomes assessed pre-post.	Goniometry to assess knee flexion/extension range of motion (ROM) and valgus/varus positioning during gait.	Knee extension and flexion ROM increased significantly during gait at 9 months post ACLR.
Capin et al. 2017 ³⁸	Participants randomized to a 10 session strength, agility, plyometric, and secondary prevention (SAPP) training or SAPP training plus perturbation training. Outcomes assessed pre-post-1yr 2yr follow up.	Limb symmetry during walking using 3D motion capture, force plates, and EMG.	Neither SAPP nor SAPP + Perturbation training improved interlimb symmetries in men at up to 2 years post ACLR.
Decker et al. 2004 ³⁹	Participants (avg. 28 yrs. old) randomized to a 6-week walking vs walking with a prescribed stride frequency (PSF) protocol. Outcomes assessed pre-post	3D motion capture and force plates to quantify hip position and knee position at heel strike, knee midstance range of motion and kinetic measures of hip extensor impulse and knee extensor impulse	Gait retraining with FHDO showed improvements in lower-extremity positions, hip and knee extensor angular impulse, and work parameters at both 6- and 12-weeks post ACLR. PSF showed no statistical improvements.
Moran et al. 2019 ⁴⁰	Participants (avg. 21 yrs. old) randomized into a neuromuscular electrical stimulation functional electrical stimulation during gait for 10 minutes 3 times per week for 4 weeks.	Comfortable gait speed and single leg stance symmetry.	No gait metrics improved significantly.
Luo et al. 2016 ⁴¹	Participants randomized into partial weightbearing treadmill training (PWBTT) or PWBTT plus traditional	10-meter walk time	10-meter walk time increased significantly in the PWTT + TPT, compared to TPT only.

Single Session Interventions			
Author	Intervention	Gait Metric	Notable Outcomes
	physical therapy (TPT). Outcomes assessed at 12 and 24 weeks after surgery.		
Hartigan et al. 2009 ⁴²	Participants randomized into strength or perturbation training + for 10 sessions prior to ACLR outcomes assessed pre intervention and 6 months post-surgery	Lower Extremity Kinematics via 3D motion analysis system	Individuals who performed perturbations + strengthening were more symmetrical than those who did strengthening only 6 months post ACLR.
Eastlack et al. 2005 ⁴³	Participants walked using lower body positive pressure once weekly for 6 weeks after surgery. Outcomes assessed after walking intervention.	EMG of the biceps femoris and vastus medialis oblique. Ground reaction forces and knee angles during gait.	Magnitude of EMG activity was maintained at all experienced lower body pressure ranges. Pain was significantly reduced, knee range of motion was larger under body weight support conditions at weeks 3 and 4 but by weeks 5 and 6 all conditions were similar
Interventions of Greater Than 12 Weeks			
Li et al. 2019 ⁴⁴	Participants were randomized to typical care or typical care + adjunct core stabilization and strengthening (1 hour per day for 6 months) program to established but unidentified ACL Rehabilitation protocol. Outcomes assessed pre-post.	3D motion analysis and force plates to assess cadence, stride length, stride width, and gait speed, knee range of motion, and peak reaction forces.	Cadence, stride length, gait speed, and knee range of motion increased over the course of the intervention. Joint peak reaction forces increased at the ankle, knee, and hip at 6 months post ACLR.

Anterior Collateral Ligament Reconstruction = ACLR, avg.=average, yrs.=years

LIMITATIONS

A limitation that may be present within this study is the use of MeSH terms that may not have aligned with translations of terms from studies written in other languages. A second limitation could be the operational definition of therapeutic interventions. For this study therapeutic intervention as a physical intervention performed by a clinician on a patient with ACLR was defined. This may have omitted other prospective interventions that, while unlikely, may have a positive effect on gait metrics such as psychological interventions or durable medical equipment such as bracing interventions.

CONCLUSION

The results of this scoping review show that few studies have tested interventions to target gait normalization after ACLR. Further, the lack of standardization of the interventions in the 14 studies, as well as variability in rehabilita-

tion duration and follow-up assessments of the interventions give rise to an important clinical problem to address. A need is present for well-vetted and widely studied therapeutic interventions that address common gait maladaptations after ACLR to address long-term knee health in individuals with ACLR.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

1. Frank CB, Jackson DW. The science of reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am.* 1997;79(10):1556-1576. doi:[10.2106/00004623-199710000-00014](https://doi.org/10.2106/00004623-199710000-00014)
2. Kaeding CC, Leger-St-Jean B, Magnussen RA. Epidemiology and diagnosis of anterior cruciate ligament injuries. *Clin Sports Med.* 2017;36(1):1-8. doi:[10.1016/j.csm.2016.08.001](https://doi.org/10.1016/j.csm.2016.08.001)
3. Paterno MV, Kiefer AW, Bonnette S, et al. Prospectively identified deficits in sagittal plane hip-ankle coordination in female athletes who sustain a second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Clin Biomech.* 2015;30(10):1094-1101. doi:[10.1016/j.clinbiomech.2015.08.019](https://doi.org/10.1016/j.clinbiomech.2015.08.019)
4. Arundale AJH, Cummer K, Capin JJ, Zarzycki R, Snyder-Mackler L. Report of the clinical and functional primary outcomes in men of the ACL-SPORTS trial: Similar outcomes in men receiving secondary prevention with and without perturbation training 1 and 2 years after ACL reconstruction. *Clin Orthop Relat Res.* 2017;475(10):2523-2534. doi:[10.1007/s11999-017-5280-2](https://doi.org/10.1007/s11999-017-5280-2)
5. Luc B, Gribble PA, Pietrosimone BG. Osteoarthritis prevalence following anterior cruciate ligament reconstruction: a systematic review and numbers-needed-to-treat analysis. *J Athl Train.* 2014;49(6):806-819. doi:[10.4085/1062-6050-49.3.35](https://doi.org/10.4085/1062-6050-49.3.35)
6. Mall NA, Frank RM, Saltzman BM, Cole BJ, Bach BR Jr. Results After anterior cruciate ligament reconstruction in patients older than 40 years: how do they compare with younger patients? A systematic review and comparison with younger populations. *Sports Health.* 2016;8(2):177-181. doi:[10.1177/1941738115622138](https://doi.org/10.1177/1941738115622138)
7. Nakamae A, Adachi N, Deie M, et al. Risk factors for progression of articular cartilage damage after anatomical anterior cruciate ligament reconstruction: a second-look arthroscopic evaluation. *Bone Joint J.* 2018;100-B(3):285-293. doi:[10.1302/0301-620X.100B3.BJJ-2017-0837.R1](https://doi.org/10.1302/0301-620X.100B3.BJJ-2017-0837.R1)
8. Oiestad BE, Holm I, Risberg MA. Return to pivoting sport after ACL reconstruction: association with osteoarthritis and knee function at the 15-year follow-up. *Br J Sports Med.* 2018;52(18):1199-1204. doi:[10.1136/bjsports-2017-097718](https://doi.org/10.1136/bjsports-2017-097718)
9. Mather RC 3rd, Koenig L, Kocher MS, et al. Societal and economic impact of anterior cruciate ligament tears. *J Bone Joint Surg Am.* 2013;95(19):1751-1759. doi:[10.2106/JBJS.L.01705](https://doi.org/10.2106/JBJS.L.01705)
10. Samuelson K, Balk EM, Sevetson EL, Fleming BC. Limited evidence suggests a protective association between oral contraceptive pill use and anterior cruciate ligament injuries in females: a systematic review. *Sports Health.* 2017;9(6):498-510. doi:[10.1177/1941738117734164](https://doi.org/10.1177/1941738117734164)
11. Ithurburn MP, Zbojniec AM, Thomas S, et al. Lower patient-reported function at 2 years is associated with elevated knee cartilage T1rho and T2 relaxation times at 5 years in young athletes after ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2019;27(8):2643-2652. doi:[10.1007/s00167-018-5291-x](https://doi.org/10.1007/s00167-018-5291-x)
12. Varady NH, Grodzinsky AJ. Osteoarthritis year in review 2015: mechanics. *Osteoarthritis Cartilage.* 2016;24(1):27-35. doi:[10.1016/j.joca.2015.08.018](https://doi.org/10.1016/j.joca.2015.08.018)
13. Andriacchi TP, Koo S, Scanlan SF. Gait mechanics influence healthy cartilage morphology and osteoarthritis of the knee. *J Bone Joint Surg Am.* 2009;91 Suppl 1(Suppl 1):95-101. doi:[10.2106/JBJS.H.01408](https://doi.org/10.2106/JBJS.H.01408)
14. Erhart-Hledik JC, Chu CR, Asay JL, Andriacchi TP. Gait mechanics 2 years after anterior cruciate ligament reconstruction are associated with longer-term changes in patient-reported outcomes. *J Orthop Res.* 2017;35(3):634-640. doi:[10.1002/jor.23317](https://doi.org/10.1002/jor.23317)
15. Kaur M, Ribeiro DC, Theis JC, Webster KE, Sole G. Movement Patterns of the Knee During Gait Following ACL Reconstruction: A Systematic Review and Meta-Analysis. *Sports Med.* 2016;46(12):1869-1895. doi:[10.1007/s40279-016-0510-4](https://doi.org/10.1007/s40279-016-0510-4)
16. Young People With Old Knees Research Team, Saxby DJ, Bryant AL, et al. Relationships between tibiofemoral contact forces and cartilage morphology at 2 to 3 years after single-bundle hamstring anterior cruciate ligament reconstruction and in healthy knees. *Orthop J Sports Med.* 2017;5(8):2325967117722506. doi:[10.1177/2325967117722506](https://doi.org/10.1177/2325967117722506)
17. Bjornsen E, Evans-Pickett A, Davis-Wilson H, et al. Peak vertical ground reaction force modifies gait biomechanics bilaterally following acl reconstruction: a randomized experiment. *J Orthop Res.* 2025;43(8):1423-1431. doi:[10.1002/jor.26101](https://doi.org/10.1002/jor.26101)

18. Gokeler A, Benjaminse A, van Eck CF, Webster KE, Schot L, Otten E. Return of normal gait as an outcome measurement in acl reconstructed patients. A systematic review. *Int J Sports Phys Ther*. 2013;8(4):441-451.
19. Andriacchi TP, Briant PL, Bevell SL, Koo S. Rotational changes at the knee after ACL injury cause cartilage thinning. *Clin Orthop Relat Res*. 2006;442:39-44. doi:[10.1097/01.blo.0000197079.26600.09](https://doi.org/10.1097/01.blo.0000197079.26600.09)
20. Khandha A, Manal K, Wellsandt E, Capin J, Snyder-Mackler L, Buchanan TS. Gait mechanics in those with/without medial compartment knee osteoarthritis 5 years after anterior cruciate ligament reconstruction. *J Orthop Res*. 2017;35(3):625-633. doi:[10.1002/jor.23261](https://doi.org/10.1002/jor.23261)
21. Pamukoff DN, Montgomery MM, Holmes SC, Moffit TJ, Garcia SA, Vakula MN. Association between gait mechanics and ultrasonographic measures of femoral cartilage thickness in individuals with ACL reconstruction. *Gait Posture*. 2018;65:221-227. doi:[10.1016/j.gaitpost.2018.07.174](https://doi.org/10.1016/j.gaitpost.2018.07.174)
22. Titchenal MR, Williams AA, Chehab EF, et al. Cartilage subsurface changes to magnetic resonance imaging ute-t2* 2 years after anterior cruciate ligament reconstruction correlate with walking mechanics associated with knee osteoarthritis. *Am J Sports Med*. 2018;46(3):565-572. doi:[10.1177/0363546517743969](https://doi.org/10.1177/0363546517743969)
23. Blackburn JT, Pietrosimone B, Harkey MS, Luc BA, Pamukoff DN. Quadriceps function and gait kinetics after anterior cruciate ligament reconstruction. *Med Sci Sports Exerc*. 2016;48(9):1664-1670. doi:[10.1249/MSS.0000000000000963](https://doi.org/10.1249/MSS.0000000000000963)
24. Harkey MS, Luc BA, Golightly YM, et al. Osteoarthritis-related biomarkers following anterior cruciate ligament injury and reconstruction: a systematic review. *Osteoarthritis Cartilage*. 2015;23(1):1-12. doi:[10.1016/j.joca.2014.09.004](https://doi.org/10.1016/j.joca.2014.09.004)
25. Pfeiffer S, Harkey MS, Stanley LE, et al. Associations between slower walking speed and t1rho magnetic resonance imaging of femoral cartilage following anterior cruciate ligament reconstruction. *Arthritis Care Res*. 2018;70(8):1132-1140. doi:[10.1002/acr.23477](https://doi.org/10.1002/acr.23477)
26. Pietrosimone B, Loeser RF, Blackburn JT, et al. Biochemical markers of cartilage metabolism are associated with walking biomechanics 6-months following anterior cruciate ligament reconstruction. *J Orthop Res*. 2017;35(10):2288-2297. doi:[10.1002/jor.23534](https://doi.org/10.1002/jor.23534)
27. Tricco AC, Lillie E, Zarin W, et al. A scoping review on the conduct and reporting of scoping reviews. *BMC Med Res Methodol*. 2016;16:15. doi:[10.1186/s12874-016-0116-4](https://doi.org/10.1186/s12874-016-0116-4)
28. Tricco AC, Lillie E, Zarin W, et al. PRISMA extension for scoping reviews (prisma-scr): checklist and explanation. *Ann Intern Med*. 2018;169(7):467-473. doi:[10.7326/M18-0850](https://doi.org/10.7326/M18-0850)
29. Arksey H, O'Malley L. Scoping studies: towards a methodological framework. *Int J Soc Res Methodology*. 2005;8(1):19-32. doi:[10.1080/1364557032000119616](https://doi.org/10.1080/1364557032000119616)
30. Alrashdi NZ, Brown-Taylor L, Bell MM, Ithurburn MP. Movement patterns and their associations with pain, function, and hip morphology in individuals with femoroacetabular impingement syndrome: A scoping review. *Phys Ther*. 2021;101(11). doi:[10.1093/ptj/pzab185](https://doi.org/10.1093/ptj/pzab185)
31. Blackburn T, Padua DA, Pietrosimone B, et al. Vibration improves gait biomechanics linked to posttraumatic knee osteoarthritis following anterior cruciate ligament injury. *J Orthop Res*. 2021;39(5):1113-1122. doi:[10.1002/jor.24821](https://doi.org/10.1002/jor.24821)
32. Hu C, Huang Q, Yu L, Ye M. The immediate intervention effects of robotic training in patients after anterior cruciate ligament reconstruction. *J Phys Ther Sci*. 2016;28(7):2031-2033. doi:[10.1589/jpts.28.2031](https://doi.org/10.1589/jpts.28.2031)
33. Hunt MA, Di Ciacca SR, Jones IC, Padfield B, Birmingham TB. Effect of anterior tibiofemoral glides on knee extension during gait in patients with decreased range of motion after anterior cruciate ligament reconstruction. *Physiother Can*. 2010;62(3):235-241. doi:[10.3138/physio.62.3.235](https://doi.org/10.3138/physio.62.3.235)
34. Luc-Harkey BA, Franz JR, Blackburn JT, Padua DA, Hackney AC, Pietrosimone B. Real-time biofeedback can increase and decrease vertical ground reaction force, knee flexion excursion, and knee extension moment during walking in individuals with anterior cruciate ligament reconstruction. *J Biomech*. 2018;76:94-102. doi:[10.1016/j.jbiomech.2018.05.043](https://doi.org/10.1016/j.jbiomech.2018.05.043)
35. Capin JJ, Zarzycki R, Ito N, et al. Gait mechanics in women of the acl-sports randomized control trial: interlimb symmetry improves over time regardless of treatment group. *J Orthop Res*. 2019;37(8):1743-1753. doi:[10.1002/jor.24314](https://doi.org/10.1002/jor.24314)
36. Capin JJ, Khandha A, Zarzycki R, Manal K, Buchanan TS, Snyder-Mackler L. Gait mechanics after acl reconstruction differ according to medial meniscal treatment. *J Bone Joint Surg Am*. 2018;100(14):1209-1216. doi:[10.2106/JBJS.17.01014](https://doi.org/10.2106/JBJS.17.01014)

37. Coury HJ, Brasileiro JS, Salvini TF, Poletto PR, Carnaz L, Hansson GA. Change in knee kinematics during gait after eccentric isokinetic training for quadriceps in subjects submitted to anterior cruciate ligament reconstruction. *Gait Posture*. 2006;24(3):370-374. doi:[10.1016/j.gaitpost.2005.11.002](https://doi.org/10.1016/j.gaitpost.2005.11.002)
38. Capin JJ, Zarzycki R, Arundale A, Cummer K, Snyder-Mackler L. Report of the primary outcomes for gait mechanics in men of the acl-sports trial: secondary prevention with and without perturbation training does not restore gait symmetry in men 1 or 2 years after acl reconstruction. *Clin Orthop Relat Res*. 2017;475(10):2513-2522. doi:[10.1007/s11999-017-5279-8](https://doi.org/10.1007/s11999-017-5279-8)
39. Decker MJ, Torry MR, Noonan TJ, Sterett WI, Steadman JR. Gait retraining after anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil*. 2004;85(5):848-856. doi:[10.1016/j.apmr.2003.07.014](https://doi.org/10.1016/j.apmr.2003.07.014)
40. Moran U, Gottlieb U, Gam A, Springer S. Functional electrical stimulation following anterior cruciate ligament reconstruction: a randomized controlled pilot study. *J Neuroeng Rehabil*. 2019;16(1):89. doi:[10.1186/s12984-019-0566-0](https://doi.org/10.1186/s12984-019-0566-0)
41. Luo Y, Shen W, Jiang Z, Sha J. Treadmill training with partial body-weight support after anterior cruciate ligament reconstruction: a randomized controlled trial. *J Phys Ther Sci*. 2016;28(12):3325-3329. doi:[10.1589/jpts.28.3325](https://doi.org/10.1589/jpts.28.3325)
42. Hartigan E, Axe MJ, Snyder-Mackler L. Perturbation training prior to ACL reconstruction improves gait asymmetries in non-copers. *J Orthop Res*. 2009;27(6):724-729. doi:[10.1002/jor.20754](https://doi.org/10.1002/jor.20754)
43. Eastlack RK, Hargens AR, Groppo ER, Steinbach GC, White KK, Pedowitz RA. Lower body positive-pressure exercise after knee surgery. *Clin Orthop Relat Res*. 2005;431:213-219. doi:[10.1097/01.blo.0000150459.92012.f7](https://doi.org/10.1097/01.blo.0000150459.92012.f7)
44. Li JX. Effects of core-stability training on gait improvement in patients after anterior cruciate ligament reconstruction. *International Journal of Clinical and Experimental Medicine*. 2019;12(5):5731-5737. doi:[10.1123/ijatt.2023-0028](https://doi.org/10.1123/ijatt.2023-0028)
45. Li J, Xie X. Effects of core-stability training on gait improvement in patients after anterior cruciate ligament reconstruction. *International Journal of Clinical and Experimental Medicine*. 2019;12(5):5731-5737.
46. Behrens F, Kraft EL, Oegema TR Jr. Biochemical changes in articular cartilage after joint immobilization by casting or external fixation. *J Orthop Res*. 1989;7(3):335-343. doi:[10.1002/jor.1100070305](https://doi.org/10.1002/jor.1100070305)
47. Wilson W, van Burken C, van Donkelaar C, Buma P, van Rietbergen B, Huijskes R. Causes of mechanically induced collagen damage in articular cartilage. *J Orthop Res*. 2006;24(2):220-228. doi:[10.1002/jor.20027](https://doi.org/10.1002/jor.20027)
48. Andriacchi TP, Mundermann A. The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. *Curr Opin Rheumatol*. 2006;18(5):514-518. doi:[10.1097/01.bor.0000240365.16842.4e](https://doi.org/10.1097/01.bor.0000240365.16842.4e)
49. Chaudhari AM, Briant PL, Beville SL, Koo S, Andriacchi TP. Knee kinematics, cartilage morphology, and osteoarthritis after ACL injury. *Med Sci Sports Exerc*. 2008;40(2):215-222. doi:[10.1249/mss.0b013e31815cbb0e](https://doi.org/10.1249/mss.0b013e31815cbb0e)
50. Kaiser JM, Vignos MF, Kijowski R, Baer G, Thelen DG. Effect of loading on in vivo tibiofemoral and patellofemoral kinematics of healthy and acl-reconstructed knees. *Am J Sports Med*. 2017;45(14):3272-3279. doi:[10.1177/0363546517724417](https://doi.org/10.1177/0363546517724417)
51. Williams JR, Neal K, Alfayyadh A, et al. Early knee loading asymmetries may be at the root of eventual osteoarthritis development after anterior cruciate ligament reconstruction. *Osteoarthritis Cartilage*. 2020;28(28(Supplement 1)):S226-S227. doi:[10.1016/j.joca.2020.02.370](https://doi.org/10.1016/j.joca.2020.02.370)
52. Koo S, Rylander JH, Andriacchi TP. Knee joint kinematics during walking influences the spatial cartilage thickness distribution in the knee. *J Biomech*. 2011;44(7):1405-1409. doi:[10.1016/j.jbiomech.2010.11.020](https://doi.org/10.1016/j.jbiomech.2010.11.020)
53. Southall K, Vogtle L, Singh H, Ithurburn MP, Bickel CS, Hurt CP. Clinicians' attitudes, perspectives, and clinical practices on gait retraining after anterior cruciate ligament reconstruction. *Int J Athl Ther Train*. 2024;1(aop):1-6. doi:[10.1123/ijatt.2023-0028](https://doi.org/10.1123/ijatt.2023-0028)
54. Teng HL, Wu D, Su F, et al. Gait characteristics associated with a greater increase in medial knee cartilage t1rho and t2 relaxation times in patients undergoing anterior cruciate ligament reconstruction. *Am J Sports Med*. 2017;45(14):3262-3271. doi:[10.1177/0363546517723007](https://doi.org/10.1177/0363546517723007)
55. Andriacchi TP, Koo S, Scanlan SF. Gait mechanics influence healthy cartilage morphology and osteoarthritis of the knee. *J Bone Joint Surg Am*. 2009;91 Suppl 1(Suppl 1):95-101. doi:[10.2106/JBJS.H.01408](https://doi.org/10.2106/JBJS.H.01408)
56. Hall M, Stevermer CA, Gillette JC. Gait analysis post anterior cruciate ligament reconstruction: Knee osteoarthritis perspective. *Gait & Posture*. 2012;36(1):56-60. doi:[10.1016/j.gaitpost.2012.01.003](https://doi.org/10.1016/j.gaitpost.2012.01.003)

57. Kaiser JM, Vignos MF, Kijowski R, Baer G, Thelen DG. Effect of loading on in vivo tibiofemoral and patellofemoral kinematics of healthy and acl-reconstructed knees. *Am J Sports Med.* 2017;45(14):3272-3279. doi:[10.1177/0363546517724417](https://doi.org/10.1177/0363546517724417)
58. Schmitz RJ, Harrison D, Wang HM, Shultz SJ. Sagittal-plane knee moment during gait and knee cartilage thickness. *J Athl Train.* 2017;52(6):560-566. doi:[10.4085/1062-2050-52.4.05](https://doi.org/10.4085/1062-2050-52.4.05)
59. Brunnekreef JJ, van Uden CJT, van Moorsel S, Kooloos JGM. Reliability of videotaped observational gait analysis in patients with orthopedic impairments. *BMC Musculoskel Disord.* 2005;6(1):17. doi:[10.1186/1471-2474-6-17](https://doi.org/10.1186/1471-2474-6-17)
60. Lin PE, Sigward SM. Subtle alterations in whole body mechanics during gait following anterior cruciate ligament reconstruction. *Gait Posture.* 2019;68:494-499. doi:[10.1016/j.gaitpost.2018.12.041](https://doi.org/10.1016/j.gaitpost.2018.12.041)
61. Schurr SA, Marshall AN, Resch JE, Saliba SA. Two-dimensional video analysis is comparable to 3d motion capture in lower extremity movement assessment. *Int J Sports Phys Ther.* 2017;12(2):163-172.
62. Munro A, Herrington L, Carolan M. Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. *J Sport Rehabil.* 2012;21(1):7-11. doi:[10.1123/jsr.21.1.7](https://doi.org/10.1123/jsr.21.1.7)
63. Weir G, Alderson J, Smailes N, Elliott B, Donnelly C. A Reliable Video-based ACL Injury Screening Tool for Female Team Sport Athletes. *Int J Sports Med.* 2019;40(3):191-199. doi:[10.1055/a-0756-9659](https://doi.org/10.1055/a-0756-9659)
64. Chen S, Lach J, Lo B, Yang GZ. Toward Pervasive Gait Analysis With Wearable Sensors: A Systematic Review. *J Biomed Health Inform.* 2016;20(6):1521-1537. doi:[10.1109/IBHI.2016.2608720](https://doi.org/10.1109/IBHI.2016.2608720)
65. Islam RBM, Nicholas K, Button K, et al. A nonproprietary movement analysis system (mojoxlab) based on wearable inertial measurement units applicable to healthy participants and those with anterior cruciate ligament reconstruction across a range of complex tasks: Validation study. *JMIR Mhealth Uhealth.* 2020;16(8):e17872. doi:[10.2196/17872](https://doi.org/10.2196/17872)
66. Li RT, Kling SR, Salata MJ, Cupp SA, Sheehan J, Voos JE. Wearable performance devices in sports medicine. *Sports Health.* 2016;8(1):74-78. doi:[10.1177/1941738115616917](https://doi.org/10.1177/1941738115616917)

SUPPLEMENTARY MATERIALS

Appendix 1

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