Postoperative Rehabilitation of Anterior Cruciate Ligament Reconstruction: A Systematic Review

Christopher Nelson, PT, DPT, Lavan Rajan, BA,† Jonathan Day, MS,† Richard Hinton, MD,‡ and Blake M. Bodendorfer, MD§‖*

Abstract: Recent studies have investigated the various components of postoperative rehabilitation protocols following anterior cruciate ligament reconstruction (ACLR). The objective of this article was to access and summarize the latest evidence for postoperative rehabilitation protocols following ACLR to evaluate common timeframes, number of phases, exercises, as well as the length of rehabilitation protocol. Common interventions include vibration training, open-chain and closed-chain exercises, electrical stimulation, postoperative bracing, and aquatic therapy. The eligibility criteria included English-language articles published from 2000 to 2019 pertaining to rehabilitation following ACLR, excluding addresses, commentaries, and editorials. Two blinded reviewers screened, graded, and extracted data from articles. Recommendations on various aspects of rehabilitation were summarized. A total of 3651 articles were retrieved from the database search, and 62 level 1 to 2 studies were available for extraction. On the basis of the evidence, vibration training can be safely incorporated into the postoperative rehabilitation protocol following ACLR. Accelerated rehabilitation may give patients short-term functional benefits. Open kinetic chain exercises may have additional strength and endurance benefits. Postoperative bracing does not confer additional benefits. Long-term use of neuromuscular electrical stimulation seems to be more beneficial than short-term use. Aquatic rehabilitation may be beneficial in the early phases of anterior cruciate ligament rehabilitation.

Key Words: ACL, anterior cruciate ligament, reconstruction, postoperative rehabilitation, guidelines

(*Sports Med Arthrosc Rev* 2021;29:63–80)

The anterior cruciate ligament (ACL) is the primary anteriorotary stabilizer of the knee and is commonly injured in sporting activities.[1,2] Although nonoperative management of ACL tear is an option, surgical repair by way of anterior cruciate ligament reconstruction (ACLR) is considered the gold standard for the goal of returning to preinjury levels.[3] During ACLR, an autograft (most commonly patellar tendon or hamstring tendon) or allograft is used to replace the damaged ACL. However, surgery alone is only 1 component of a successful treatment program. An effective rehabilitation program after ACLR is necessary to restore comprehensive function to the joint and to return the patient to preinjury activity levels without an increased risk of reinjury. Many clinical trials have investigated various aspects of postoperative ACL rehabilitation programs, such as the length of the rehabilitation program, the role of specific exercises, frequency of rehabilitation sessions, and more.[1,2,4–18] However, previous systematic reviews on this topic have not included results from the most recent randomized controlled trials (RCTs) which provide new, valuable information. In addition, there are still many controversies regarding the use of certain interventions in a rehabilitation program for ACLR patients. In this systematic review, we examined the rehabilitation protocols that were used in recent RCTs and synthesized their results to display common timeframes, number of phases, and exercises shared by the protocols. We also analyzed these studies and focused on common evidence-based interventions to discover what the current research supports. These interventions include the length of rehabilitation protocol (traditional vs. accelerated), vibration training, open kinetic chain (OKC) versus closed kinetic chain (CKC) exercises, electrical nerve stimulation, postoperative bracing, and aquatic versus land rehabilitation. Primary clinical outcomes included knee stability, quadriceps and hamstring strength, knee joint laxity, and patient-reported functional outcomes.

PATIENTS AND METHODS

Eligibility Criteria

Studies were included for assessment if they were published from the year 2000 to the present, and if they contained rehabilitation protocols or discussed specific aspects of rehabilitation protocols for patients who underwent ACLR. Exclusion criteria included nonoperative management of ACL injury, multiligament injuries, concomitant meniscal injury or meniscectomy, other joint procedures that were not ACLR, or animal models. In addition, studies that compared surgical techniques or did not focus on rehabilitation protocols were excluded. Addresses, comments, and editorials were excluded.

Information Sources

We conducted a search within PubMed, Embase (via Ovid), Web of Science Core Collection, SPORTDiscus (via EBSCOhost), CINAHL (via EBSCOhost), Cochrane Central Register of Controlled Trials (via Ovid), Cochrane Database of Systematic Reviews (via Ovid), ClinicalTrials.gov, and PEDro from the year 2000 to June 18, 2019.

From the *MedStar Health Physical Therapy at Irving Street Orthopedic Center, National Rehabilitation Hospital; †Georgetown University School of Medicine; §Orthopaedic Surgery Residency Program, Georgetown University Hospital, Washington, DC; ‡Department of Orthopedic Surgery, MedStar Sports Medicine, MedStar Union Memorial Hospital, Baltimore, MD; and ‖Rush University Medical Center, Midwest Orthopedics at Rush, Chicago, IL.

The authors declare no conflict of interest.

Reprints: Christopher Nelson, PT, DPT, 120 20th Street, Suite 116, NW Building 1, North, Washington, DC 20036. E-mail: chrisnelson202@gmail.com.

Supplemental Digital Content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's website, www.sportsmedarthro.com.

Search

A health sciences librarian developed the search strategy utilizing a combination of keywords and database-specific subject headings related to each concept including anterior cruciate ligament, surgical repair, and rehabilitation. Please refer to the Supplemental Digital Content 1 document for complete and reproducible search strategies (http://links.lww.com/SMAR/A33). Case reports, commentaries, and editorials were excluded from the search, as well as non-English and nonhuman studies. We removed duplicates using EndNote X9 (Clarivate Analytics, Philadelphia, PA).

Data Collection Process

Articles found in the literature search went through 2 rounds of reviews using Rayyan QCRI (Doha, Qatar) by 2 independent, blinded reviewers. In the first review, articles were included if they contained information on rehabilitation after ACLR in the title or abstract. These included articles then moved on to the second round of review, which involved a full-text screen. Articles were included if they discussed rehabilitation protocols following ACLR. After the 2 reviewers marked their respective articles for inclusion, blinding was turned off, and a third independent reviewer resolved any conflicts.

After the full-text screening, included articles were graded for their levels of evidence by 2 independent, blinded reviewers. A third independent reviewer resolved any conflicts in the levels of evidence.

Once the final article bank was completed, full PDF files of all included articles were reviewed on Rayyan. Data from each article were extracted and recorded on a working Dropbox file by 2 team members.

Summary of Measures and Results

The principal summary measure was the level of evidence. RCTs were considered level 1. Systematic reviews and meta-analyses were also considered level 1 if they included level 1 studies in their research. Prospective cohort studies were considered level 2. Retrospective case-control studies were considered level 3. Case-series were considered level 4. Expert opinions, editorials, and review articles without critical appraisal were considered level 5.

Data from the final selection of articles were independently extracted by 2 reviewers. For each article, data regarding the study goals, adverse events, rehabilitation phases, rehabilitation, and follow-up timeframe, rehabilitation exercises, study results, and conclusions were extracted.

Risk of Bias

To reduce the risk of bias in the data collection and synthesis, a standardized protocol, described above, was utilized. All articles that met the inclusion and exclusion criteria were screened in a blinded manner for inclusion in the final article bank to limit any interobserver bias. A conventional, previously defined methodology for objectively grading levels of evidence was utilized. For quality

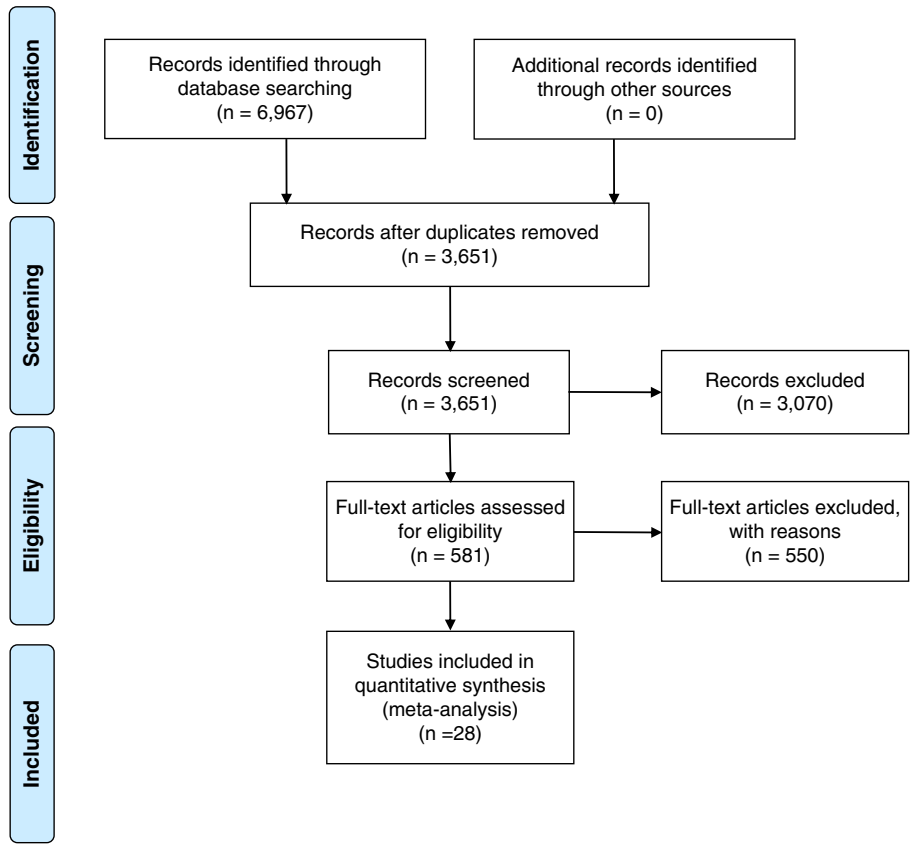

FIGURE 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram highlighting search strategy and extraction of included articles. full color online

Copyright © 2021 Wolters Kluwer Health, Inc. All rights reserved.

purposes, only level 1 and 2 articles were included in the final review.

RESULTS

Study Selection

There were 3651 articles retrieved from the database search. After the first review, 581 articles were included. After the second review, 62 studies were included. Of the included articles, 51 were level 1 studies, and 11 were level 2 studies. Level 4 and 5 articles were excluded. During the final review, 16 additional articles were removed because they included patients who had meniscus surgeries. In the final synthesis of the articles, 18 level 1 studies that were systematic reviews or meta-analyses were excluded to narrow the focus to RCTs and to eliminate redundancy of summarizing articles that were previously extracted in our search. After the final review, 28 articles were included. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram in Figure 1 outlines the review process.

Study Characteristics

The study characteristics and patient demographics are presented in Table 1. Data from 2131 patients are included in this systematic review. For each study, the demographics and preoperative characteristics were extracted. These included: level of evidence, number of patients, mean patient age, study design, inclusion criteria, exclusion criteria, surgical technique, and risk factors. The postoperative management and outcome characteristics for which data were extracted are the study goals, adverse events, rehabilitation phases, rehabilitation, and follow-up timeframe, rehabilitation exercises, study results, and conclusions.

Synthesis of Results

Patient Demographics

The number of patients included in each study ranged from 14 to 145 with an average of 52.8 patients. The mean age of the patients ranged from 20.3 to 35.6 years. Eight studies only included male patients, 1 study included only female athletes, and the remaining 19 articles either included male and female patients or did not specify sex. For inclusion criteria, 15 articles specifically listed ACLR, 7 articles listed an isolated ACL tear with no concomitant injury, and 4 articles listed moderate preoperative activity based on Tegner score as well as no prior history of ACLR. Common exclusion criteria listed in 12 articles included concurrent injury to other ligaments, concomitant meniscal or osteochondral injury. Seven additional articles excluded patients with a previous ACL or other lower extremity surgery. Of the articles that specified surgical technique for ACLR, 11 studies used patellar tendon grafts, 12 studies used hamstring tendon grafts (semitendinosus and gracilis), and 3 studies included patients with patellar tendon grafts, as well as patients with hamstring tendon grafts.

Postoperative Protocols (Initial Phases)

The postoperative interventions are presented in Table 2. Twenty-three studies described rehabilitation protocols and divided them into phases. The number of phases ranged from 1 to 9. Most commonly, protocols were divided into 4 phases. The timeframe of the protocols ranged from 12 weeks to 1 year. The length of phase 1 ranged from 2 to 5 weeks, while the length of phase 2 ranged from 2 to 12 weeks. Certain trends were identified in the organization of rehabilitation protocol phases. During phase 1, 10 studies included isometric quadriceps and hamstrings exercises. Nine studies promoted passive and active range of motion (ROM) exercises to increase knee flexion and extension. Eight studies mentioned the use of cryotherapy and cold therapy. Five studies used transcutaneous electric nerve stimulation (TENS)/neuromuscular electrical stimulation (NMES), had patients perform straight leg raises, utilized a knee brace, and promoted weight-bearing as tolerated. An additional 4 studies implemented hip abduction and adduction exercises, knee and patella mobilization, gait training, and ankle exercises. Regarding phase 2, 8 studies promoted progressive neuromuscular training and proprioception exercises. Seven studies discussed continued active and passive ROM exercises to promote full knee ROM. Progressive resistance training, including leg press, calf press, and step-ups, were recommended by 6 studies. Five studies implemented endurance training using a stationary bicycle, stair stepper, or treadmill. Two additional studies promoted discontinuation of the brace.

Postoperative Protocols (Late Phases)

Phase 3 ranged from 2 to 24 weeks long and phase 4 ranged from 2 to 12 weeks long. During phase 3, 6 studies discussed the progression of proprioceptive training and balance exercises. Five studies introduced running. Four additional studies had patients performing plyometric exercises and jump training. In phase 4, 5 studies used progressive resistance training. Four studies implemented sport-specific neuromuscular control and proprioception training. Three studies performed sport-specific exercises. Two studies utilized agility drills, sprinting, cutting drills, and plyometrics. Depending on the protocol, phase 4 and beyond was used for a gradual return to sport participation for athletes.

Adverse Events

Adverse events occurred in 9 of the studies. One study examining the difference between home physical therapy and supervised physical therapy had 1 patient in the physical therapy group who sustained a rupture of the ACL graft and required revision surgery.[18] The authors did not specify how the patient ruptured their graft or whether the rehabilitation protocol caused the rupture.[18] The same study had 4 patients that required arthroscopic debridement for mechanical symptoms and pain, as well as 2 patients that required manipulation under anesthesia.[18] One study had 2 patients that were lost due to "possible deep vein thrombosis" following surgery.[33] Both of the patients in this study were in the placebo group and no details are provided on whether or not they had a confirmed diagnosis of deep vein thrombosis.[33] This study also had 2 patients in the experimental group and 2 patients in the placebo group drop out due to "gastrointestinal distress" from the supplements administered.[33] An additional study had 2 patients develop anterior arthrofibrosis that required surgery to remove cyclops lesions.[24] The rest of the adverse events were due to patients dropping out of the study for reasons unrelated to the knee, the graft, or the surgery.

TABLE 1. Patient Demographics, Level of Evidence, Study Design, Preoperative Information

References	Level of Evidence	No. Patients	Other Patient Information	Study Design	Mean Age (y)	Inclusion Criteria	Exclusion Criteria	Surgery Technique/ Details
The effects of balance training on static and dynamic postural stability indices sfter acute ACL reconstruction[19]	1	48	24 patients with ACLR, 24 controls without ACLR; all patients were male	RCT	Control group: 20.33 ± 10.9 Experimental group: 22.33 ± 11.03	ACLR, 4 wk postoperative, men, 16-35 y, BMI of 17-25, able to balance on single leg, healthy sensory motor function	Ankle pain, involved in sports, vertigo, uncorrected visual problems knee injury or leg surgery, taking sedatives, cardio/ neuro/pulmonary disease, balance problems rhematoid disease, fracture and contracture, osteoporosis, OA, psychological disease	ACLR—graft not specified
The SpeedCourt system in rehabilitation after reconstruction surgery of the anterior cruciate ligament (ACL)[20]	1	50	All patients were athletes; 14 females and 36 males	RCT	SpeedCourt: 31.4 ± 7.48 Control: 34.4 ± 12.5	No specific inclusion criteria listed	No specific exclusion criteria listed	ACLR—quadruple bundled hamstring-transplant
Effectiveness of lateral slide exercise in an anterior cruciate ligament reconstruction rehabilitation home exercise program[21]	1	14	12 male and 2 female patients	RCT	35.6 ± 10.6	Older than 18 y of age, ACLR	No specific exclusion criteria listed	ACLR—patella tendon autograft
Improvement of posture stability by vibratory stimulation following anterior cruciate ligament reconstruction[22]	1	30	All male patients	RCT, double-blind	25 ± 3	No specific inclusion criteria listed	Previous knee injury	Arthroscopic all-inside ACLR using semitendinosus and gracilis
The effect of functional movement training after anterior cruciate ligament reconstruction: a randomized controlled trial[23]	1	38	19 patients in the exercise group, 19 patients in the control group	RCT	Exercise group: 26 Control group: 27	ACLR—hamstring autografts from January 2014 to December 2015	Other musculoskeletal problems in legs, combined ACLR with other surgery, unstable physical fitness level or inability to exercise, or surgical complications	Arthroscopic single-bundle ACLR using hamstring autograft
The effects of early aggressive rehabilitation on outcomes after anterior cruciate ligament reconstruction using	1	36	19 patients in the aggressive group, 17 patients in the nonaggressive group	RCT	Aggressive group: 30.1 ± 10.5 Nonaggressive group: 33.1 ± 10.9	18-55 y, grade 2 or 3 ACL tear, moderately active preoperatively, full knee extension, 85% knee flexion, compliance, English speaking	Any previous ACLR to either knee, chondral lesions with an outerbridge grade of > 2, concurrent injury to the PCL, a grade 3 tear of LCL or MCL,	ACLR—single-bundle ipsilateral 4-strand semitendinosus-gracilis autograft

autologous hamstring tendon: a randomized clinical trial[24]							meniscus tears ≥ 5 mm or meniscus repairs, pregnancy, workers' compensation, neurological disorders affecting participation	
Efficacy of whole-body vibration board training on strength in athletes after anterior cruciate ligament reconstruction: a randomized controlled study[14]	1	38	All female volleyball/ basketball players	RCT, double-blind	Control group: 25.42 ± 2.39 WBV group: 25.47 ± 2.01	ACL rupture in female volleyball or basketball player between 20-30 y; sports activity for at least 6 y before the injury; first ACL surgery	Any concomitant ligament or meniscus injury; previous orthopedic lower limb surgery; evidence of chondral lesion higher than grade 2; any injury to the contralateral knee or lower limb	ACLR—patella tendon autograft
The effectiveness of supplementing a standard rehabilitation program with superimposed neuromuscular electrical stimulation after anterior cruciate ligament reconstruction: a prospective, randomized, single-blind study[25]	1	96	Males and females	RCT, single-blind	Control: 31.6 ± 1.36 Polystim: 34.8 ± 1.49 Kneehab: 31.1 ± 1.52	Isolated rupture of the ACL, between ages 18 and 55, no additional injury to the knee	ACL tear > 6 mo old, previous injury or surgery of the injured knee, tears of the menisci, articular cartilage defects larger than International Cartilage Repair Society grade 2	ACLR—semitendinosus and gracilis grafts
Adding high-frequency transcutaneous electrical nerve stimulation to the first phase of post anterior cruciate ligament reconstruction rehabilitation does not improve pain and function in young male athletes more than exercise alone: a randomized single-blind clinical trial[6]	1	70	Male athletes. Thirty-five patients in the control group. Thirty-five patients in the TENS group	RCT, single-blind	Control group: 26.31 ± 4.33 TENS group: 26 ± 4.1	Male athletes with ACLR; age 18-45, involvement of only one extremity, no TENS risk factors, no previous surgery, no psych or systemic disease	Not being able to tolerate the intervention, violation of any one of the inclusion criteria, not willing to continue participation in the study	ACLR—BPTB graft

TABLE 1. (*continued*)

References	Level of Evidence	No. Patients	Other Patient Information	Study Design	Mean Age (y)	Inclusion Criteria	Exclusion Criteria	Surgery Technique/ Details
Safety, feasibility, and efficacy of negative work exercise via eccentric muscle activity following anterior cruciate ligament reconstruction[26]	1	32	Sixteen patients in the control group. Sixteen patients in the eccentric group. Nine males and 7 females per group	RCT, matched design	Eccentric group: 29.4 ± 9.4 Traditional group: 31.0 ± 9.8	18-50 y old, > 4 points on Tegner, compliance	Previous fracture or reconstructive procedure, abnormal findings on the radiograph, concurrent injury of PCL or LCL, grade 3 MCL tear, large articular cartilage lesion, large meniscus tear	ACLR—semitendinosus-gracilis or BPTB autograft
Two- to 4-y follow-up to a comparison of home versus physical therapy-supervised rehabilitation programs after anterior cruciate ligament reconstruction[18]	1	88	The original study had 129 patients. Only 88 patients returned for long-term follow-up. Male and female patients	RCT	Home: 30.8 ± 10.1 at baseline; 34.0 ± 10.0 at follow-up PT: 30.3 ± 11.1 at baseline; 33.4 ± 11.0 at follow-up	16 y of age or older; surgery at least 6 wk after injury; ACLR with BPTB autograft	Previous or concomitant reconstruction of any knee ligament to either knee; ongoing knee abnormality unrelated to an ACL injury (evidence of osteoarthritis on radiographs); professional athletes or workers' compensation patients; complications during surgery; patients without access to local PT	ACLR—BPTB graft
Comparison of home versus physical therapy-supervised rehabilitation programs after anterior cruciate ligament reconstruction: a randomized clinical trial[27]	1	145	73 patients in the home group, 72 patients in the PT group; only 129 patients returned for the 12-wk follow-up. Male and female	RCT	Home group: 29.1 ± 9.2 PT group: 29.5 ± 10.2	16 y or older; surgery at least 6 wk after injury; ACLR with BPTB	Previous or concomitant reconstruction of any knee ligament to either knee; ongoing knee abnormality unrelated to ACL; professional athletes or workers' comp; surgical complications; patients without access to local PT	ACLR—BPTB autograft
Cross-education improves quadriceps strength recovery after ACL reconstruction: a randomized controlled trial[28]	1	48	16 patients evenly distributed in all 3 groups; sex not specified	RCT	Concentric cross-education (CE): 29.7 ± 6.9 Eccentric CE: 30.4 ± 7.5 Control: 28.1 ± 6.1	Unilateral arthroscopic ACLR with hamstring tendon; age 17-45; noncontact injury; preinjury tegner score ≥ 5; regular continuation of PT program	ACLR with patellar tendon autograft or allograft; revision for ACLR; ACLR with meniscus and/or cartilage repair; systemic or neurological problems; lower extremity injuries in contralateral lower extremity within the prior 12 mo	ACLR—hamstring tendon autograft

Physiotherapy-guided versus home-based, unsupervised rehabilitation in isolated anterior cruciate injuries following surgical reconstruction[29]	1	40	20 patients in each group; male and female patients	RCT	Physiotherapy group: 28 Home group: 27	Isolated ACL injury <3 mo old; contact and noncontact injuries during sports	Additional injuries to menisci, MCL, LCL, PCL, and articular cartilage; injuries to ipsilateral or contralateral lower extremity and patients involved in MVA; the significant side-to-side difference in varus/valgus instability	ACLR—BPTB graft
Comparison of strength and endurance between open and closed kinematic chain exercises after anterior cruciate ligament reconstruction: randomized control trial[5]	1	36	Patients were evenly distributed between the 2 groups; 12 males and 6 females each	RCT, prospective single-blind	OKC group: 29.9 ± 2.3 CKC group: 29.0 ± 4.0	ACLR patients participating in a 3-mo rehabilitation between May 2009 and October 2011	Subjects with orthopedic or neurological problems subjects who did not receive intervention in the previous 12 wk	ACLR—graft not specified
A comparative study of whole body vibration training and conventional training on knee proprioception and postural stability after anterior cruciate ligament reconstruction[16]	1	20	The study originally had 40 patients. Twenty were excluded. The remaining 20 patients were evenly distributed between the 2 groups. The patients were all male athletes	RCT	WBVT group: 24.51 ± 3.38 conventional training group: 22.70 ± 3.77	3 mo s/p ACLR; competitive athletes; no previous or concomitant injury or surgery on knee or other joints; no history of surgery or traumatic injuries to contralateral limb; full ROM in knee; no contraindications for WBVT	WBVT contraindications, medical problems such as heart disease that limit activity participation	ACLR—BPTB graft
Cross-exercise on quadriceps deficit after ACL reconstruction[30]	1	42	Male soldiers in the Greek army. Patients evenly distributed among the 3 groups	RCT	Cross-exercise group (3 d/wk): 23.64 ± 2.56 Cross-exercise group: (5 d/wk): 25.07 ± 2.40 Control group: 23.14 ± 2.71	20-25 y old, complete ACL rupture within 40 d to 6 mo; at least 3 mm of bilateral difference in the anterior knee joint laxity; abnormal or severely abnormal knee function; 0-5 in recreational or sports activities on Tegner	Clinical varus/valgus laxity or symptomatic meniscal injuries; painful knee ROM; joint swelling, leg length discrepancy, cartilage lesions, fractures, history of lower extremity pain in last 6 mo	ACLR—arthroscopically assisted autograft with semitendinosus and gracilis
Effects of closed versus open kinetic chain knee extensor resistance training on knee laxity and leg function in patients during the 8- to 14-wk postoperative period after anterior cruciate ligament reconstruction[17]	1	49	37 males, 12 females. Twenty-five patients in the CKC group, 24 patients in the OKC group	RCT	CKC group: 33 ± 8 OKC group: 33 ± 7	No prior contralateral injury within 6 mo; no PCL injury in the operated knee; 18-60 y	Prior contralateral injury within 6 mo, PCL injury in the operated leg	ACLR—arthroscopic and open BPTB grafts or arthroscopic semitendinosus/gracilis grafts depending on the surgeon

TABLE 1. (*continued*)

References	Level of Evidence	No. Patients	Other Patient Information	Study Design	Mean Age (y)	Inclusion Criteria	Exclusion Criteria	Surgery Technique/ Details
Comparison of an innovative rehabilitation, combining reduced conventional rehabilitation with balneotherapy, and a conventional rehabilitation after anterior cruciate ligament reconstruction in athletes[7]	1	67	Amateur and professional athletes. Males and females in each group	RCT	Conventional group: 29.91 ± 7.70 Experimental group: 28.22 ± 7.38	Amateur or professional athletes; chronic knee instability and an indication of ACLR	History of neurological disease, medication for psychotropic or antihypertensive; contraindications to aquatic activities, recent sprains interfering with postural control	ACLR—semitendinosus/ gracilis or patellar tendon
The long-term effect of 2 postoperative rehabilitation programs after anterior cruciate ligament reconstruction: a randomized controlled clinical trial with 2 y of follow-up[31]	1	74	27 females, 47 males	RCT, single-blind	28.4	ACL BPTB graft; 15-40 y of age	ACL tear > 3 y before surgery; meniscal tear; previous injury/ surgery to either knee; articular cartilage fissures extending to subchondral bone; exposed bone intraoperatively	ACLR—BPTB graft
Neuromuscular training versus strength training during first 6 mo after anterior cruciate ligament reconstruction: a randomized clinical trial[32]	1	74	27 females, 47 males	RCT, single-blind	28.4	ACL BPTB graft; 15-40 y of age	ACL tear > 3 y before surgery; meniscal tear; previous injury/ surgery to either knee; articular cartilage fissures extending to subchondral bone; exposed bone intraoperatively	ACLR—BPTB graft
Mechanical vibration in the rehabilitation of patients with reconstructed anterior cruciate ligament[4]	1	20	17 males and 3 females	RCT	Treatment: 29.7 ± 7.8 Control: 26.8 ± 5.2	No specific inclusion criteria listed	No specific exclusion criteria listed	ACLR—half tunnel technique with patella tendon autologous transplant
The effect of creatine supplementation on strength recovery after anterior cruciate ligament (ACL) reconstruction: a randomized, placebo-controlled, double-blind trial[33]	1	60	33 males, 27 females	RCT, double-blind, prospective	30.4 ± 1.0	No specific inclusion criteria listed	No specific exclusion criteria listed	ACLR—BPTB graft

The effects of rehabilitation protocol on functional recovery after anterior cruciate ligament reconstruction[34]	2	70	Male patients evenly distributed between both groups	Prospective cohort	Group A: 26.77 ± 7.17 Group B: 26.97 ± 7.22	No specific inclusion criteria listed	No specific exclusion criteria listed	ACLR—arthroscopic hamstring graft
Does an accelerated program give equivalent results in both elite athletes and nonathletes?[13]	2	30	15 athletes, 15 nonathletes; male and female participants	Prospective preintervention-postintervention design	Athlete group: 24.25 ± 3.55 Nonathlete group: 27.60 ± 5.69	Unilateral ACLR, age 20-40, maximum of 4 wk in the presurgery period after the injury	Meniscal reconstruction during the ACLR session, or concurrent ligament injury, or any major postoperative complication	ACLR—autologous hamstring tendon graft
The effect of proprioception exercises on functional status in patients with anterior cruciate ligament reconstruction[35]	2	36	20 injured participants, 16 age-matched and sex-matched healthy volunteers	Case-control	Injured: 28.7 ± 8.5 Control: 31.06 ± 8.4	No specific inclusion criteria listed	Previous surgery to same knee, concurrent injury, deformity or pathology of ankle/hip; injury <6 mo	ACLR—autologous hamstring tendon graft
Evaluation of gait kinematics and symmetry during the first 2 stages of physiotherapy after anterior cruciate ligament reconstruction[36]	2	97	53 ACLR patients and 44 healthy patients; sex not specified	Prospective Comparative study	ACLR group: 31.5 ± 9.6 Control group: 23.1 ± 9.6	All males with completely torn ACLs due to amateur sports who had undergone ACLR with ST/G	No specific exclusion criteria listed	ACLR—semitendinosus and gracilis
Longitudinal changes of neuromuscular quadriceps function after reconstruction of the anterior cruciate ligament[37]	2	31	8 ACLR patients, 23 controls Experimental group: Male athletes with ACLR	Cohort study	Experimental group: 29 ± 9 Control group: 22 ± 2	Male athletes with a complete, isolated, first-time ACL tear	Concomitant injuries, bilateral ACL injuries, former knee or ligament injuries in either extremity that might affect the outcomes	ACLR—doubled semitendinosus and gracilis tendons

ACLR indicates anterior cruciate ligament reconstruction; BPTB, bone-patellar tendon-bone; CKC, closed kinetic chain; LCL, lateral collateral ligament; MCL, medial collateral ligament; OKC, open kinetic chain; PCL, posterior cruciate ligament; RCT, randomized controlled trial; ROM, range of motion; WBV, whole-body vibration.

TABLE 2. Postoperative Information, Numbers of Phases in Protocols, Exercises, Results, Conclusions

References	Postoperative Details	Goals	# Phases	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5+	Timeframe	Exercises	Results	Conclusions
A comparative study of whole body vibration training and conventional training on knee proprioception and postural stability after ACLR[16]	Twenty athletes with unilateral ACLR were randomly assigned to the WBVT or conventional training group	To compare the effects of a WBVT program with conventional therapy on knee proprioception and postural stability	9	WBVT: 30 Hz Strengthening (control): 3 sets of 10 RM for hip abductors and adductors	WBVT: 30 Hz Control: 3 sets of 10 RM for hip abductors, adductors and flexors	WBVT: 30 Hz Control: 3 sets of 10 RM for hip abductors, adductors, flexors and extensors	WBVT: 35 Hz Control: 4 sets of 10 RM for hip abductors, adductors, flexors, extensors, leg press	WBVT: 35-50 Hz Control: 3-4 sets of 10 RM or fraction of body weight	12 wk	WBVT: Various squat positions; lunge; toe standing Control: hip extensors, flexors, abductors, adductors, mini squats, squats, leg press, leg curls	The improvement in postural stability in the WBVT group was significantly greater than that in the conventional training group	WBVT was associated with a greater improvement of joint stability and balance
Adding high-frequency transcutaneous electrical nerve stimulation to the first phase of post ACL reconstruction rehabilitation does not improve pain & function in young male athletes more than exercise alone[6]	A randomized single-blind (exercise instructor and assessor) clinical trial was performed on 70 male athletes who had undergone ACL surgery	To study whether TENS could help athletes perform better during the first phase of rehabilitation after ACLR	1	0-4 wk In the intervention group, a TENS apparatus was used around the painful area on the knee for 20 sessions	NA	NA	NA	NA	14 wk	Supine knee extension, prone heel hangs, supine wall slides, quadriceps/ hamstring sets, cocontraction, heel slides, PREs leg press, heel rises, bicycle, step-ups, gait training, weight shifting, and joint mobilization	Both groups improved significantly regarding all outcome measures after 4 and 14 wk. There was not a significant interaction effect of time and group on all outcome measures	High-frequency TENS during the first phase of post-ACLR surgery rehabilitation did not lead to any further effect
Comparison of an innovative rehabilitation, combining reduced conventional rehabilitation with balneotherapy, and a conventional rehabilitation after ACLR in athletes[7]	67 patients, who were amateur or professional athletes, were randomized into 2 groups	To compare a protocol combining conventional rehabilitation with aquatic rehabilitation, with a conventional rehabilitation	3	Conventional rehabilitation protocol for both groups	Three weeks of experimental/ innovative protocol for the experimental group	Return to conventional protocol	NA	NA	6 mo	No specific exercises listed	Patients who followed the innovative protocol had less lateralization at the contralateral side and greater muscle strength of the hamstrings and quadriceps	This study shows that the innovative rehabilitation protocol improves proprioception and limits overcompensation on the limb contralateral to the operated limb
Comparison of home versus physical therapy–supervised rehabilitation programs after anterior cruciate ligament reconstruction[27]	145 patients who attended a presurgery education class. Home-based patients attended 4 PT sessions, and physical therapy–supervised patients attended 17 PT sessions	To determine if there were differences in patient outcome between home-based rehabilitation and traditional physical therapy–supervised rehabilitation	4	No specific exercises listed	No specific exercises listed	No specific exercises listed	No specific exercises listed	NA	12 wk	No specific exercises listed	The home-based group had a significantly higher percentage of patients with acceptable ROM	A minimally supervised rehabilitation program was more effective in achieving acceptable knee ROM in the first 3 mo than a standard physical therapy program
Comparison of strength and endurance between open and closed kinematic chain exercises after anterior cruciate ligament reconstruction[5]	36 postoperative ACL patients evenly distributed between OKC and CKC groups	To compare the strength and endurance benefits of OKC and CKC exercise therapies after ACLR	1	All exercises were done in 5 sets of 12 repetitions each at 70% intensity of 1 RM	NA	NA	NA	NA	12 wk	OKC: SLR, leg extension, CKC: leg curls, squats, leg press, lunge	OKC exercises showed a significantly greater difference in isokinetic strength and endurance of the extensor muscles compared with CKC	OKC exercise is helpful for the strength and endurance of the knee extensor mechanism after ACLR and can be effectively used in a rehabilitation program

Cross-education improves quadriceps strength recovery after ACL reconstruction: a randomized controlled trial[28]	Forty-eight patients who had undergone ACLR with hamstring tendon autograft were randomly divided into 3 groups when they reached 4 wk postsurgery	To investigate the effects of concentric and eccentric CE on quadriceps strength and knee function after ACLR	3	0-4 wk: Limit swelling obtain full knee ROM, achieve good quadriceps control, normalize gait	4-12 wk: Progressive neuromuscular training mostly performed in weight-bearing	12-24 wk: Resistive hip and knee strengthening, plyometrics, running, and balance exercises	NA	NA	6 mo	Specific exercises are listed on the online appendix	Quadriceps strength of both knees was greater in concentric and eccentric groups compared with control	Concentric and eccentric quadriceps strengthening of healthy limbs improved postsurgical quadriceps strength recovery
Cross-exercise on quadriceps deficit after ACL reconstruction[30]	Participants consisted of male patient soldiers in the Greek army with unilateral ACL ruptures confirmed by magnetic resonance imaging and clinical examination	To evaluate the effects of cross-eccentric exercise (CEE) on quadriceps deficit on ACLR knees, and to explore any changes in quadriceps deficit following CEE	3	2-4 wk: SLR, early ROM exercise with an emphasis on gaining full knee extension, WBAT, static squat	2-3 mo: Endurance training (biking), progressive resistance training, dynamic squat, balance exercises, eccentrics, PREs, isokinetics	3-6 mo: Continued PREs Jogging/running, swimming, eccentrics, strengthening and functional exercise training	NA	NA	6 mo	See phase columns	An increase of quadriceps strength was evident for the uninjured knees across the groups postoperatively, in contrast to the injured knees	CEE used as supplementary to the ACL traditional rehabilitation program in the early stages improves quadriceps muscle strength deficit
Does an accelerated program give equivalent results in both elite athletes and nonathletes?[13]	Prospective preintervention-postintervention design. Fifteen elite athletes and 15 nonathletes who underwent unilateral ACLR with autologous hamstring tendon graft	To examine the effects of the same accelerated anterior cruciate ligament rehabilitation program on pain and functionality of elite athletes and nonathletes	3	0-2 wk: Ice and elevation, NMES during active isometric quadriceps exercises, ankle pumps, passive full knee extension and hamstring stretch, SLR, Quadriceps set, CPM, education, brace use at 0 degrees	2-4 wk: No brace, WBAT, CPM, quadriceps isometrics, patella mobs, leg press, SLR, mini squat, hamstring and calf stretch, NMES during quadriceps contraction, AROM/PROM flexion, scar massage, ice, proprioception, treadmill	4-8 wk: Full ROM, patella mobs, SLR, OKC knee extension, half squat, wall squat, leg press, lateral step-up, static bicycle, TKE hamstring curls, calf raises, proprioception training, scar massage, treadmill	NA	NA	8 wk	See phase columns	Significant improvement detected for pain, knee flexion range, Lysholm score, and beck depression inventory	The same accelerated rehabilitation protocol provides significant improvements for pain, functionality, and depression in both elite athletes and nonathletes after ACLR
Effectiveness of lateral slide exercise in an anterior cruciate ligament reconstruction rehabilitation home exercise program[21]	Fourteen subjects who underwent patella tendon autograft reconstruction on one of their ACLs were studied	To determine the effect of incorporating lateral slide exercise into an ACLR rehabilitation, home exercise program	6	Week 1: 5×1 min with a 1-min rest between sets	Week 2: 5×3 min with a 2-min rest between sets	Week 3: 5×4 min with a 2-min rest between sets	Week 4: 5×5 min with a 3-min rest between sets	Week 5: 3×10 min with a 3-min rest between sets Week 6: 3×12 min with a 3-min rest between sets	6 wk	See phase columns	Significant improvements in the slide group for quadriceps strength while the control group showed no significant increase	Including lateral slide exercise in a home exercise program after ACLR seems to improve knee extension strength
Effects of closed versus open kinetic chain knee extensor resistance training on knee laxity and leg function in patients during the 8- to 14-wk postoperative period after anterior cruciate ligament reconstruction[17]	The study subjects were 49 patients recovering from ACLR surgery. Tests were carried out at 8 and 14 wk after ACLR with knee laxity measured using a ligament arthrometer and function	The purpose of this study was to compare the effects of the 2 regimens on knee laxity and function in the 8-to-14-wk period after ACLR	2	0-4 wk: Three sets of 20 RM were used in each session until the beginning of week 4 of the 6-wk intervention period, whereupon a switch to 3 sets of 6 RM was instituted	See phase 1 column	NA	NA	NA	6 wk	Leg press, knee extensor machine, hip extensor, hamstring curl machine	Results from this study indicate that the OKC and CKC training programs do not differ significantly in their effects on knee laxity in the 8- to 14-wk period after ACLR surgery	Continue using only CKC training after ACLR surgery, as OKC training does not seem to offer any particular advantages over CKC training in patients who have had ACLR, and the evidence that exists about its harmfulness has not been fully refuted
Efficacy of whole-body vibration board training on strength in athletes after	Thirty-eight female volleyball/basketball players (aged	To evaluate the short-term effects of an 8-wk WBV training program on knee flexion/	6	1-2 wk: WBAT with crutches, cryotherapy and leg elevation, Knee and	3-4 wk: Same as prior phase plus hip and hamstring isotonics, double	5-8 wk: Same as previous phase plus single-leg proprioception, Squatting,	9-12 wk: Same as previous phases plus jump training (2 legs	13-16 wk: Same as previous phases plus Isokinetic strength	26 wk	See phase columns	Improvements were noticed in both groups, but an increase in knee muscle	When combined with a standardized rehabilitation program, WBV may increase muscular

TABLE 2. (*continued*)

References	Postoperative Details	Goals	# Phases	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5+	Timeframe	Exercises	Results	Conclusions
anterior cruciate ligament reconstruction: a randomized controlled study[14]	between 20 and 30), randomized into 2 treatment groups	extension muscular strength among female athletes after arthroscopic ACLR with patellar tendon		patellar mobilization, CPM, isometrics, NMES, hamstring stretching	leg proprioception	Cycling, hydrotherapy, and swimming	on a trampoline)	exercises/ test, Plyometric and agility training, WBV additional protocol, running			isokinetic strength values was statistically significant in the WBV group when compared with the control	strength and be an effective additional treatment option
Evaluation of gait kinematics and symmetry during the first 2 stages of physiotherapy after anterior cruciate ligament reconstruction[36]	Ninety-seven males, including 53 patients after primary ACLR in 1 limb and 44 healthy controls, participated in the study. The patients were examined using a movement analysis system	To evaluate selected parameters of gait kinematics and symmetry in male patients after ACLR on 3 occasions during the first 2 stages of their physiotherapeutic program	2	0-5 wk: Cryotherapy, CPM, isometrics, gait training, HEP, mobilization of the patellofemoral joint and lateral thigh, glute and iliolumbar strengthening, electrical stimulation to quadriceps, proprioception	6-12 wk: ROM exercises, hamstring strengthening, gait training, ergometer, treadmill, stepper, proprioception	NA	NA	NA	12 wk	See phase columns	Consistent improvement in all gait parameters for ACLR group over the course of the study with final numbers close to or equal to the noninjured control group	Improvement was noted in gait kinematics and symmetry compared with the control group. Improvements in velocity, step frequency and step length. Improvements were also noted in ROM, gait symmetry indices and stance time
Improvement of posture stability by vibratory stimulation following anterior cruciate ligament reconstruction[22]	Thirty men who had ACLR were studied in a double-blind procedure	To determine the effect of the vibratory method in ACLR patients on postural control when standing on the operated or nonoperated leg, and on the extensor torque of both legs	6	1-7 d: Brace locked at 0 degrees, NWB, SLR cryotherapy, and ankle pumps	8-20 d: Brace removed, AROM and PROM knee flexion to 90, active and passive stretching, SLR, cryotherapy	After 21 d: Independent gait, SLR with increased weight	After 40 d: Proprioception exercises	After 60 d: linear running and, progressively, running with changes of direction. After 90 d: Light sport activity	270 d	The experimental technique consisted of applying vibratory stimulation on/ over the skin overlying the distal part of the quadriceps	A short-lasting vibratory treatment improves the single-limb standing balance and the extensor muscle torque on the operated side of subjects that had undergone ACLR	This study possibility of producing rehabilitation of a joint by directly acting on the plastic properties of the central nervous system
Longitudinal changes of neuromuscular quadriceps function after reconstruction of the anterior cruciate ligament[37]	MVC torque and femoral nerve stimulation were used to measure quadriceps strength and voluntary activation (VA) deficits in both legs of 10 subjects with ACLR	To determine the longitudinal time course of changes in quadriceps strength and inhibition after ACLR	None	NA	NA	NA	NA	NA	48 wk	Immediate FWB, full knee extension, PROM up to 90 degrees, quadriceps exercises, strengthening, knee mobilization, gait, NMES, proprioception, and water exercises	The results showed significant changes over time of the involved quadriceps for MVC	MVC and VA fully reflect the functional status of the quadriceps muscle recovery during rehabilitation
Mechanical vibration in the rehabilitation of patients with reconstructed anterior cruciate ligament[4]	20 subjects were randomly divided into 2 groups. Ten experimental and 10 control	Evaluate the usefulness of mechanical vibration in the rehabilitation of patients who received ACLR	5	1-2 wk: 2 crutches, knee and patella mobs, isometrics, e-stim, ischiocrural stretching, cryotherapy	3-4 wk: Same as previous phase plus 1 crutch, weight shifting, isotonic hip and ischiocrural	5-8 wk: Same as previous plus hip, quadriceps and ischiocrural exercise, waist massage, bipedal	9-12 wk: same as previous plus isotonic quadriceps exercise, walking,	13-16 wk: Same as previous plus isokinetics and running	16 wk	See phase columns	The treatment group showed a mean increase in muscle strength and in mean force peaks	This treatment can be useful in the rehabilitation of ACLR patients

Copyright © 2021 Wolters Kluwer Health, Inc. All rights reserved.

					exercise, shoulder massage	proprioception, exercise bike	cycling, swimming					
Neuromuscular training versus strength training during first 6 mo after anterior cruciate ligament reconstruction: a randomized clinical trial[32]	The study was a randomized, single-blinded, controlled trial	The purpose of this study was to determine the effect of a 6-mo neuromuscular training (NT) program vs. strength training (ST) program following ACLR	6	NT group: See appendix ST group: ROM exercises, stationary bicycle, cold therapy	NT group: See appendix ST group: Weight-bearing during the exercises was emphasized to normalize gait and to control knee movements	NT group: See appendix: ST group: Moderate-intensity to high-intensity ST. After 13 to 16 wk, treadmill running	NT group: See appendix. ST group: ST exercises and sport-specific exercises	NT group: See appendix	6 mo	See appendix	The NT group demonstrated improved Cincinnati Knee Scores and VAS score compared with the ST group	The results of this study suggest that exercises included in the NT program should be part of the rehabilitation program following ACLR
Physiotherapy-guided versus home-based, unsupervised rehabilitation in isolated anterior cruciate injuries following surgical reconstruction[29]	Forty patients with isolated anterior cruciate ligament injuries were allocated to either a supervised physiotherapy intervention group or a home-based exercise group	The purpose of this study was to investigate outcomes after ACLR between a group of patients receiving a standardized PT rehabilitation program vs. home-based program	5	0-2 wk: Brace locked in extension at night, Open brace 0-90 degrees during the day, weight-bearing as tolerated	2-6 wk: Gentle squats standing in 30-60 degrees of flexion, exercise bike at 50 watts, calf raises and hamstring curls	6-12 wk: Increase resistance on the bike to 100 watts, step-ups, half squats, standing 1 leg (balance work) pool exercises	3-6 mo: Skipping sideways, step-ups, calf raises, jogging, sprints, running backward, noncontact sport-specific drills	6 mo+: No contact sports until 9 mo after surgery	12 mo	See phase columns	Both groups improved significantly following 12 mo after surgery	This study could not demonstrate a benefit in a rehabilitation program supervised by a physiotherapist in the population compared with an unsupervised cohort
Safety, feasibility, and efficacy of negative work exercise via eccentric muscle activity following anterior cruciate ligament reconstruction[26]	Beginning 3 wk after ACLR, 32 participants were randomly assigned into either a 12-wk traditional (TRAD) or ECC exercise program	To evaluate the short-term safety and efficacy of adding a progressive negative work exercise program via ECC ergometry early after ACLR	3	2-3 wk: ROM exercises. WBAT or TTWB, SLR, and gait training. Week 1 of eccentrics: Session 1, very, very light RPE. Session 2 very light RPE. Session 3 fairly light RPE	2-3 mo: Endurance training, PREs. Week 2 of eccentrics: Session 4 Light RPE. Sessions 5-6 somewhat hard RPE	3-6 mo: Continued PREs Jogging, advanced plyometric exercises, advanced strengthening and functional exercise. Weeks 3-4 of eccentrics, sessions 7-12 somewhat hard RPE	Weeks 5-6 of eccentrics: Sessions 13-18, somewhat hard RPE, 20-25 min	Weeks 7-8 of eccentrics: 19-24 Somewhat hard RPE, 26-30 min Weeks 9-12 of eccentrics: Sessions 25-36, hard RPE, 26-30 min	26 wk	See phase columns	There were no significant differences between groups in measures of knee and thigh pain, effusion, or stability at any period after surgery	Negative work via an ECC intervention was implemented safely after ACLR. The addition of negative work exercise also induced superior short-term results in strength, performance, and activity
The effect of creatine supplementation on strength recovery after anterior cruciate ligament reconstruction: A randomized, placebo-controlled, double-blind trial[33]	Sixty patients were randomized into creatine or placebo groups	The purpose of this study was to examine the effect of oral creatine supplementation on the recovery of muscle strength after ACLR	None	NA	NA	NA	NA	NA	12 wk	See the corresponding column	There were significant increases in strength and power on the involved side	The results demonstrate that patients do not benefit from creatine supplementation during the first 12 wk of rehabilitation after ACLR
The effect of functional movement training after anterior cruciate ligament reconstruction: a aandomized controlled trial[23]	A total of 38 patients who underwent ACLR were recruited and randomly assigned to groups 1 or 2	A rehabilitation program integrating FMS, FMS-based functional exercise, and routine rehabilitation was designed, and evaluated	9	0-2 wk: Hip abduction and adduction, toe raises, SLR, PROM to 0 degrees, PWB, knee brace, IFC, hot pack, ultrasound	2-4 wk: Hip abduction and adduction, toe raises, SLR, quadriceps sets, PROM to 30 degrees, PWB, knee brace, IFC, hot pack, ultrasound	4-6 wk: Same as previous with PROM to 60 degrees	6-8 wk: Same as previous with gait training, mini squats, abdominal, back, and core strengthening, PROM to 90	8-12 wk: Same as previous	6 mo	The FMS-based functional exercise was a set of gradually progressing corrective training exercises designed with reference to previous studies	Both groups had significantly increased FMS, Lysholm, and IKDC 2000 scores	The application of FMS-based functional exercise to patients after ACLR resulted in significant improvement in knee function and movement
The Effect of proprioception exercises on functional status in patients with anterior cruciate ligament reconstruction[35]	Twenty male patients, diagnosed with a unilateral ACL injury and scheduled for reconstruction, participated in the study along with 16 age-matched and sex-	To assess the effect of ACL injury on proprioception and to evaluate the effectiveness of a rehabilitation program consisting mainly of proprioception exercises	6	Early-stage (0-2 wk): Cold application, elevation, ankle movement, 4-way SLR, isometrics	Inter-stage (3-5 wk): Wall slide, heel slides, cycling, single leg balance, heel walks, toe walks, walking backward, straight line walk with eyes closed, 4-way SLR with weight	Early functional stage (6-8 wk): FWB, active knee flexion, cycling exercises, increased proprioception difficulty	Inter-functional stage (9-12 wk): Lateral and backwards walking, carioca, resistive strengthening, walking training in the pool	Late functional stage (13-19 wk): Propriocep-tive training is increased. Jumping and plyometric exercise	24 wk	See phase columns	A significant improvement was found in pain severity, proprioception, and functional capacity after the rehabilitation program	The rehabilitation program predominantly consisting of proprioception exercises provided considerable improvement on knee proprioception and functional status

TABLE 2. (*continued*)

References	Postoperative Details	Goals	# Phases	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5+	Timeframe	Exercises	Results	Conclusions
	matched healthy volunteers											
The effectiveness of supplementing a standard rehabilitation program with superimposed neuromuscular electrical stimulation after anterior cruciate ligament reconstruction[25]	Ninety-six patients, of a total enrolled cohort of 131 patients randomized to 1 of 3 intervention groups, completed a standard rehabilitation program	To assess the effectiveness of combining each of 2 forms of NMES therapy superimposed on volitional contractions with a standard postoperative rehabilitation program of volitional exercises	5	0-3 wk: Passive full knee extension, active knee flexion 0-90 degrees, voluntary quadriceps control, patella mobilization, PWB	4-6 wk: Full extension, gradual knee flexion restoration, FWB, gait training, balance, and proprioceptive exercises, cycling, aquajogging, CKC exercises	7-9 wk: Strengthening emphasis on quadriceps. Isolated quadriceps training, cycling, aquajogging, perturbation, proprioception, running, jumping	10-12 wk: PREs, isolated quadriceps training, proprioception, agility drills, and plyometrics	16-24 wk: Continue strength training. Increase endurance, OKC quadriceps, proprioception, agility, plyos, running, cutting, jumping	6 mo	See phase columns	The Kneehab group achieved significantly better results at each time point compared with the polystim and control groups	Intensive garment-integrated stimulation combined with standard rehabilitation is effective at accelerating recovery after knee surgery
The effects of balance training on static and dynamic postural stability indices after acute ACL reconstruction[19]	24 patients who had ACLR and 24 healthy adults without any knee injury were recruited in the study	To evaluate the effect of balance program in postural stability during the early phase of rehabilitation after ACLR	None	NA	NA	NA	NA	NA	2 wk for each participant	Single leg stance with eyes closed and opened, step-ups	Static stability indices did not change after training and there were no significant differences in indices before and after training	Balance exercise could partially improve dynamic stability indices in the early stage of ACLR rehabilitation
The effects of early aggressive rehabilitation on outcomes after anterior cruciate ligament reconstruction using autologous hamstring tendon: a randomized clinical trial[24]	Thirty-six patients who had a primary ACLR with a STG autograft from a single orthopedic surgeon were prospectively randomized into 2 groups	To compare the effect of early aggressive rehabilitation between 2 groups of patients after ACLR with STG autograft on the amount of anteroposterior knee laxity at 12 wk and IKDC score at 12 and 24 wk	4	Phase I (0-4 wk): PROM, AAROM, AROM exercises; stationary bike; muscle-activation; and inflammation, CPM, brace, variable whole-body status depending on research group	Phase II (4-8 wk): progressive ROM exercises, muscle strengthening, neuromuscular training, and functional activities Nonaggressive group did not start phase II exercises until week 6	Phase III (8-12 wk): Consisted of restoring full symmetrical passive ROM, increased muscle strengthening, higher level neuromuscular-control tasks, and running	Phase IV (12-24 wk): Involved progressive muscle strengthening, sport-specific neuromuscular-control training, plyometrics, sprinting, and cutting drills	NA	24 wk	See phase columns and the online appendix	There was no difference found between the groups in respect to laxity, ROM, PIF, or IKDC	No differences were found between early aggressive and nonaggressive rehabilitation after an isolated ACLR using STG autografts for the primary or secondary outcomes
The effects of rehabilitation protocol on functional recovery after anterior cruciate ligament reconstruction[34]	70 males after ACLR using a hamstring graft. Patients were divided into 2 groups according to the manner of conducting the postoperative rehabilitation	To show the effects of the rehabilitation protocol on functional recovery of patients after ACLR	4	NA	NA	NA	NA	NA	20 wk	Cryotherapy, NMES, stretching and strengthening, proprioception, functional training, and gait reeducation	Thigh muscle circumference is statistically significant. Tegner Lysholm score is statistically highly significant in patients from the experimental group	The protocol results in a significant increase of the thigh muscle circumference and faster functional recovery of patients after ACLR
The long-term effect of 2 postoperative rehabilitation programs after	Seventy-four patients were randomly assigned to either a NE	To examine the long-term outcome of a 6-mo NE training program vs. a	6 phases for NE, 4 phases for SE	NA	NA	NA	NA	NA	24 mo	NE Program The NE program: balance exercises, dynamic joint stability,	No significant differences between the NE and SE for the primary	On the basis of these results, a postoperative program combining both NE and SE

MedStar Health Lafayette Research

anterior cruciate ligament reconstruction a randomized controlled clinical trial with 2 y of follow-up[31]	(neuromuscular) program or a SE (traditional strength) program and tested preoperatively and at 6 mo, 1 y, and 2 y after ACLR	traditional SE training program after ACLR								plyometrics, agility drills, and sport-specific exercises. SE Program: strength training exercises of the lower extremity muscles	outcome measure. NE group improved knee function and reduced pain during activity and improved hamstring muscle strength	should be included after ACLR to improve knee function
The Speedcourt system in rehabilitation after reconstruction surgery of the anterior cruciate ligament (ACL)[20]	50 athletic patients were randomized and followed either a new training with the SpeedCourt or underwent a regular stabilization program	To prove if rehabilitation with unexpected disturbance programs has a benefit compared with regular sensomotoric-based concepts after arthroscopic ACLR	None listed. Participants completed the experiment 5 mo postoperative for 3 wk	NA	NA	NA	NA	NA	3 wk	The SpeedCourt exercises comprised mostly running Control group: The stabilization training was standardized. Different unstable and uneven surfaces were incorporated	In between the 2 groups, 5 of 22 parameters (23%) showed significant influences	Interventional training programs with the SpeedCourt system seem to be advantageous in the late rehabilitation following ACL-knee surgery compared with current sensomotoric-based concepts
Two- to 4-y follow-up to a comparison of home versus physical therapy-supervised rehabilitation programs after anterior cruciate ligament reconstruction[18]	Patients were randomized before ACLR surgery to either the physical therapy–supervised (17 physical therapy sessions) or home-based (4 physical therapy sessions) program	To determine whether there were any differences in long-term outcomes between athletes who performed physical therapy–supervised rehabilitation and those who performed primarily home-based rehabilitation	None	NA	NA	NA	NA	NA	2-4 y	None	The home-based group had a significantly higher mean ACL quality of life score than the physical therapy group	Patients who participate in a predominantly home-based rehabilitation program have similar 2- to 4-y outcomes compared with those patients who participate in a more supervised program

ACL indicates anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; AROM, active range of motion; AAROM, active-assisted range of motion; CKC, closed kinetic chain; CPM, continuous passive motion; FMS, Functional Movement Screen; IKDC, International Knee Documentation Committee; IFC, interferential current; MVC, maximum voluntary contraction; NA, not available; NE, neuromuscular exercise; NMES, neuromuscular electrical stimulation; PIF, peak isometric force; PREs, progressive resistance exercises; PROM, passive range of motion; PT, physical therapy; PWB, partial weight-bearing; RPE, rating of perceived exertion; RM, repetition maximum; ROM, range of motion; SE, strength exercise; SLR, straight leg raise; STG, semitendinosus and gracilis; TENS, transcutaneous electric nerve stimulation; VAS, Visual Analog Scale; WBV, whole-body vibration; WBVT, whole-body vibration training.

DISCUSSION

Summary of Evidence

Our analysis of the level 1 and 2 articles elucidated trends regarding several debated topics in ACL rehabilitation. The topics discussed in this section are accelerated rehabilitation timelines, vibration training, OKC versus CKC exercises, electrical nerve stimulation, postoperative bracing, and aquatic rehabilitation.

Accelerated Rehabilitation

One RCT from our search results studied the effects of length of rehabilitation protocols on our outcomes of interest. Feyzioglu et al[13] studied the short-term effects of a 6-week long accelerated protocol on athletes and nonathletes and found that both groups had significant improvements in pain score, knee ROM, and Lysholm score, all measured 8 weeks after surgery This study demonstrates that an accelerated rehabilitation program can have beneficial short-term effects on our clinical outcomes of interest. There is also an added psychosocial benefit as patients in the accelerated protocol had a significant improvement in the Beck Depression Inventory.[13] This improvement in depression scores shows that postoperative patients following this protocol have a higher quality of life in the short term.[13] However, further research needs to be done comparing accelerated and nonaccelerated programs and their long-term clinical outcomes and postrehabilitation injury rates in isolated ACLR patients.

Vibration Training

Whole-body vibration (WBV) training can be easily integrated into a traditional or accelerated ACL rehabilitation protocol, and several of the reviewed studies demonstrate significant improvement in muscular strength and joint stability more than traditional therapy alone. WBV is a neuromuscular training apparatus that introduces mechanical oscillations through the body at a frequency up to 50 Hz.[16] WBV is able to stimulate the body with "a variation of gravitational acceleration."[14] The variation in acceleration is similar to what can be expected during power, strength, and plyometric exercises.[14] WBV is likely beneficial because of the neuroplasticity that is present after ACLR, which comes from the loss of the mechanoreceptors present on the original ACL and subsequent inflammation.[15] Our search resulted in 3 RCTs that specifically examined the use of vibration therapy as an independent variable in ACL rehabilitation. Costantino et al[14] studied the effects of an 8-week long WBV training protocol in female volleyball and basketball players who underwent ACLR. The 8 weeks of WBV were integrated into weeks 13 to 21 of a 6-month long rehabilitation program. When compared with the control group, the WBV group had a statistically significant increase in knee muscle isokinetic strength.[14] Moezy et al[16] compared the effects of WBV therapy to conventional therapy as part of an ACL rehabilitation program. The authors found that WBV therapy resulted in a significantly greater improvement in postural stability when compared with conventional therapy.[16] Finally, an RCT done by Salvarani et al[4] administered 2 weeks of WBV to ACLR patients as part of a 16-week rehabilitation program. The WBV group showed a significant mean increase in muscle strength and force peaks, demonstrating that mechanical vibration can be used in the rehabilitation of ACLR.[4]

OKC Versus CKC Exercises

The comparative efficacy of OKC and CKC exercise is a controversial topic in ACLR rehabilitation. During OKC exercises, the distal aspect of the leg is free to move and not fixed to an object. The opposite is true for CKC exercises. The distal aspect of the leg is fixed to an object, such as the floor or a machine. CKC exercises decrease anterior shear on the tibia. This has led the implementation of CKC exercises over OKC in ACL rehabilitation due to their perceived safety.[5] Our search resulted in 2 RCTs that compared both types of exercise. Perry et al[17] found that there were no significant differences between OKC and CKC exercises in knee laxity improvement when used in the period of 8 to 14 weeks after ACLR. Patients underwent testing for knee laxity and function at week 8 postoperatively.[17] Knee laxity was assessed with the Knee Signature System.[17] Then, the patients underwent either OKC or CKC training for 6 weeks and were reassessed at week 14.[17] No significant differences in knee laxity or function were found when OKC or CKC exercises were used in this middle period of rehabilitation.[17] Kang et al[5] studied the same interventions in ACLR patients; however, this study was done on patients who had already been undergoing rehabilitation for 3 months. OKC or CKC exercises were done for a total of 12 weeks and the outcomes measured were isokinetic strength, endurance, and squat strength.[5] After 12 weeks, the OKC group showed a significantly greater increase in isokinetic strength and endurance of the extensor muscles than the CKC group did. The findings from this study suggest that OKC exercises are superior to CKC exercises for extensor strength endurance when used in the late period of rehabilitation.[5] In summary, OKC exercises seem to be more effective in terms of improving muscle strength and endurance without causing a negative impact on knee laxity when implemented 8 to 12 weeks postoperatively. More research needs to be done regarding this issue before clinical decisions regarding the use of OKC exercises in the early phases of rehabilitation are made.

Electrical Nerve Stimulation

Two RCTs in our search explored the use of electrical nerve stimulation in rehabilitation after ACLR. Forogh et al[6] studied the use of TENS for 35 minutes a day during the first 4 weeks after ACLR for pain management and muscle function. The outcomes of pain, ROM, and knee function measured by the International Knee Documentation Committee (IKDC) were measured after the 4 weeks, and at the end of the second phase of the rehabilitation program 14 weeks after surgery. There were no significant differences between the group that used TENS and the group that did not use TENS for all outcomes at both time points.[6] However, in another RCT done by Feil et al[19] electrical stimulation was used to determine its effectiveness on improving knee extensor strength and functional performance over the span of 12 weeks.[25] The participants were instructed to apply the electrical stimulation 3 times a day for 20-minute increments. The use of a novel garment-integrated NMES (Kneehab; Kneehab XP, Manassas, VA) was shown to achieve consistently better results for extensor strength and hop testing when compared with conventional NMES and rehabilitation without NMES.[25] The Kneehab group also showed "a significant difference in mean improvement for the baseline corrected Lysholm score compared with the control group."[25] The authors report

that the Kneehab patients were 10% more compliant with their home use than the conventional NMES group.[25] In summary, short-term use of supplemental NMES does not seem to yield any additional benefits for knee pain, ROM, or knee function.[6] However, long-term use of supplemental NMES does seem to be more effective than standard rehabilitation alone to improve quadriceps strength and does not negatively affect joint laxity (KT-1000).[25] The use of the novel garment-integrated NMES has demonstrated greater efficacy in improving knee function than standard rehabilitation and traditional NMES, and its use in a post-ACLR rehabilitation protocol should be studied more.

Postoperative Bracing

An RCT by Christensen et al[24] compared the effect of "early aggressive" rehabilitation and "nonaggressive" rehabilitation in ACLR patients with semitendinosus grafts on anteroposterior knee laxity at 12 weeks postoperative, and patient-reported functional outcomes (IKDC score) at 12 and 24 weeks postoperative. Patients in the "early aggressive" group did not use any postoperative brace and began weight-bearing as tolerated immediately after surgery, compared with the "nonaggressive" group who did use a postoperative brace for the first month after surgery. They found no differences between early aggressive and nonaggressive rehabilitation for these primary outcomes at both time points, demonstrating that use of a postoperative brace early in the rehabilitation period did not have an effect on anteroposterior laxity and self-reported functional outcome.[24] This evidence was summarized in several later systematic reviews which concluded, with strong to moderate evidence, that postoperative bracing does not result in significant changes in functional outcomes measures in the pediatric and adult populations following ACLR.[8,11,12,38,39]

Role of Aquatic Rehabilitation

One RCT evaluated the role of water-based exercises in postoperative rehabilitation following ACLR. In this study, 67 patients were randomized to a conventional or a combined conventional and aquatic rehabilitation protocol, starting at day 15 following the index procedure.[7] Patients were evaluated at multiple intervals in terms of proprioceptive skills and functional improvement. The investigators observed greater improvements in proprioception for the first 2 months in the aquatic rehabilitation group, which equilibrated after. In addition, the aquatic rehabilitation group demonstrated greater quadriceps and hamstring strength at 6 months, as well as greater walking distance at 1 month postoperatively. These findings suggested that the addition of aquatic exercises to conventional rehabilitation may allow for faster recovery and earlier return to activities, as well as limiting overcompensation in the uninvolved limb.[7] Overall, this study suggests there may be some benefit for aquatic rehabilitation, especially in the early postoperative period.

Limitations

Our study is not without limitations. As is the nature of most systematic reviews, the inclusion of published articles often involves an element of publication bias.[40] The results often depend on search criteria, literature sources, as well as inclusion and exclusion criteria.[40] Objective inclusion and exclusion criteria, as well as grading of the levels of evidence, were all performed by 2 blinded reviewers to minimize bias.

The exclusion of studies that involved concomitant meniscus injuries led to the removal of numerous RCTs from our final review. To isolate the effectiveness of an ACLR rehabilitation protocol, it was necessary to omit any studies with concomitant injuries. However, the mechanism of injury for an ACL tear can commonly lead to additional injury to the surrounding structures, such as the collateral ligaments, posterior cruciate ligament, or the menisci. The removal of these studies did limit the amount of data that could be extracted from our literature search.

There are also emerging trends in treating patients with ACL injuries that are not discussed due to a current lack of strong evidence. These newer methods include ACLR with quadriceps tendon autograft and blood flow restriction training. ACL repair with and without internal brace augmentation is also not discussed because the aim of this study was to focus solely on rehabilitation after ACLR.

CONCLUSIONS

In summary, there are general guidelines that can be drawn from the existing literature with regards to postoperative rehabilitation following ACLR. There is strong evidence for the added benefit of vibration training in improving in muscle strength and joint stability compared with standard rehabilitation alone. There is also strong evidence that postoperative bracing does not confer an additional benefit and may only incur additional cost to the patient.

In terms of accelerated rehabilitation protocols, there is weak evidence that these have beneficial short-term effects on clinical outcomes. However, none of the studies in our search demonstrated long-term clinical benefits of accelerated rehabilitation in isolated ACLR patients. Both open and CKC exercises can be performed by patients 2 to 3 months postoperatively, with moderate evidence supporting OKC over CKC for strength and function. There is no clear indication for the use of OKC exercises in the early phases of rehabilitation. There is moderate evidence that aquatic rehabilitation can be beneficial when performed in the early phase of rehabilitation. Finally, there is moderate evidence that garment-integrated NMES can be beneficial for improving quadriceps strength and endurance.

REFERENCES

1. Strobel M, Stedtfeld H, Eichhorn H. *Diagnostik des kniegelenkes*. Berlin, Germany: Springer-Verlag; 2013.
2. Dargel J, Gotter M, Mader K, et al. Biomechanics of the anterior cruciate ligament and implications for surgical reconstruction. *Strategies Trauma Limb Reconstr*. 2007;2:1–12.
3. Paschos NK, Howell SM. Anterior cruciate ligament reconstruction: principles of treatment. *EFORT Open Rev*. 2016; 1:398–408.
4. Salvarani A, Agosti M, Zanre A, et al. Mechanical vibration in the rehabilitation of patients with reconstructed anterior cruciate ligament. *Eura Medicophys*. 2003;39:19.
5. Kang H, Jung J, Yu J. Comparison of strength and endurance between open and closed kinematic chain exercises after anterior cruciate ligament reconstruction: randomized control trial. *J Phys Ther Sci*. 2012;24:1055–1057.
6. Forogh B, Aslanpour H, Fallah E, et al. Adding high-frequency transcutaneous electrical nerve stimulation to the first phase of post anterior cruciate ligament reconstruction rehabilitation does not improve pain and function in young male athletes more than exercise alone: a randomized single-blind clinical trial. *Disabil Rehabil*. 2019;41:514–522.
7. Peultier-Celli L, Mainard D, Wein F, et al. Comparison of an innovative rehabilitation, combining reduced conventional

rehabilitation with balneotherapy, and a conventional rehabilitation after anterior cruciate ligament reconstruction in athletes. *Front Surg*. 2017;4:61.
8. Kruse LM, Gray B, Wright RW. Rehabilitation after anterior cruciate ligament reconstruction: a systematic review. *J Bone Joint Surg*. 2012;94:1737–1748.
9. Kruse LM, Gray BL, Wright RW. Anterior cruciate ligament reconstruction rehabilitation in the pediatric population. *Clin Sports Med*. 2011;30:817–824.
10. Wright RW, Preston E, Fleming BC, et al. ACL reconstruction rehabilitation: a systematic review part II. *J Knee Surg*. 2008; 21:225–234.
11. Indorato D, Sturgil R. An assessment of rehabilitation protocols following anterior cruciate ligament reconstruction: a systematic review. *Rehab Process Outcome*. 2016;2016:RPO. S40054-64.
12. Lobb R, Tumilty S, Claydon LS. A review of systematic reviews on anterior cruciate ligament reconstruction rehabilitation. *Phys Ther Sport*. 2012;13:270–278.
13. Feyzioglu O, Ozturk O, Sirmen B, et al. Does an accelerated program give equivalent results in both elite athletes and nonathletes? *J Sport Rehabil*. 2019;1:1–6.
14. Costantino C, Bertuletti S, Romiti D. Efficacy of whole-body vibration board training on strength in athletes after anterior cruciate ligament reconstruction: a randomized controlled study. *Clin J Sport Med*. 2018;28:339–349.
15. Grooms D, Page S, Nichols-Larsen D, et al. Neuroplasticity associated with anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2017;47:180–189.
16. Moezy A, Olyaei G, Hadian M, et al. A comparative study of whole body vibration training and conventional training on knee proprioception and postural stability after anterior cruciate ligament reconstruction. *Br J Sports Med*. 2008;42:373–385.
17. Perry M, Morrissey M, King J, et al. Effects of closed versus open kinetic chain knee extensor resistance training on knee laxity and leg function in patients during the 8- to 14-week postoperative period after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2005;13:357–369.
18. Grant J, Mohtadi N. Two to four-year follow-up to a comparison of home versus physical therapy-supervised rehabilitation programs after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2010;38:1389–1394.
19. Feil S, Newell J, Minogue C, et al. The effectiveness of supplementing a standard rehabilitation program with superimposed neuromuscular electrical stimulation after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2011;39: 1238–1247.
20. Wright RW, Haas AK, Anderson J, et al. Anterior cruciate ligament reconstruction rehabilitation. *Sports Health*. 2015;7: 239–243.
21. van Grinsven S, van Grinsven S, van Cingel R, et al. Evidence-based rehabilitation following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2010;18: 1128–1144.
22. Dalton JE, Bolen SD, Mascha EJ. Publication bias: the elephant in the review. *Anesth Analg*. 2016;123:812–813.
23. Akbari A, Ghiasi F, Mir M, et al. The effects of balance training on static and dynamic postural stability indices after acute ACL reconstruction. *Glob J Health Sci*. 2015;8:68–81.
24. Christensen J, Goldfine L, West H. The effects of early aggressive rehabilitation on outcomes after anterior cruciate ligament reconstruction using autologous hamstring tendon: a randomized clinical trial. *J Sport Rehabil*. 2013;22:191–201.
25. Bartels T, Proeger S, Brehme K, et al. The SpeedCourt system in rehabilitation after reconstruction surgery of the anterior cruciate ligament (ACL). *Arch Orthop Trauma Surg*. 2016; 136:957–966.
26. Blanpied P, Carroll R, Douglas T, et al. Effectiveness of lateral slide exercise in an anterior cruciate ligament reconstruction rehabilitation home exercise program. *J Orthop Sports Phys Ther*. 2000;30:602–611.
27. Brunetti O, Filippi GM, Lorenzini M, et al. Improvement of posture stability by vibratory stimulation following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2006;14:1180–1187.
28. Chao WC, Shih JC, Chen KC, et al. The effect of functional movement training after anterior cruciate ligament reconstruction: a randomized controlled Trial. *J Sport Rehabil*. 2018;27: 541–545.
29. Gerber JP, Marcus RL, Dibble LE, et al. Safety, feasibility, and efficacy of negative work exercise via eccentric muscle activity following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2007;37:10–18.
30. Grant JA, Mohtadi NG, Maitland ME, et al. Comparison of home versus physical therapy-supervised rehabilitation programs after anterior cruciate ligament reconstruction: a randomized clinical trial. *Am J Sports Med*. 2005;33: 1288–1297.
31. Harput G, Ulusoy B, Yildiz TI, et al. Cross-education improves quadriceps strength recovery after ACL reconstruction: a randomized controlled trial. *Knee Surg Sports Traumatol Arthrosc*. 2019;27:68–75.
32. Hohmann E, Tetsworth K, Bryant A. Physiotherapy-guided versus home-based, unsupervised rehabilitation in isolated anterior cruciate injuries following surgical reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2011;19:1158–1167.
33. Tyler T, Nicholas S, Hershman E, et al. The effect of creatine supplementation on strength recovery after anterior cruciate ligament (ACL) reconstruction: a randomized, placebo-controlled, double-blind trial. *Am J Sports Med*. 2004;32:383–388.
34. Papandreou M, Billis E, Papathanasiou G, et al. Cross-exercise on quadriceps deficit after ACL reconstruction. *J Knee Surg*. 2013;26:51–58.
35. Risberg MA, Holm I. The long-term effect of 2 postoperative rehabilitation programs after anterior cruciate ligament reconstruction: a randomized controlled clinical trial with 2 years of follow-up. *Am J Sports Med*. 2009;37:1958–1966.
36. Risberg MA, Holm I, Myklebust G, et al. Neuromuscular training versus strength training during first 6 months after anterior cruciate ligament reconstruction: a randomized clinical trial. *Phys Ther*. 2007;87:737–750.
37. Dragicevic-Cvjetkovic D, Jandric S, Bijeljac S, et al. The effects of rehabilitation protocol on functional recovery after anterior cruciate ligament reconstruction. *Med Arch*. 2014;68:350–352.
38. Ordahan B, Küçükşen S, Tuncay İ, et al. The effect of proprioception exercises on functional status in patients with anterior cruciate ligament reconstruction. *J Back Musculoskelet Rehabil*. 2015;28:531–537.
39. Winiarski S, Czamara A. Evaluation of gait kinematics and symmetry during the first two stages of physiotherapy after anterior cruciate ligament reconstruction. *Acta Bioeng Biomech*. 2012;14:91–100.
40. Zech A, Awiszus F, Pfeifer K. Longitudinal changes of neuromuscular quadriceps function after reconstruction of the anterior cruciate ligament. *Current Orthopaedic Practice*. 2009;20:276–280.