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## Appendix I: Search Strategy

**PubMed Search Strategy:** ((((("Anterior Cruciate Ligament Reconstruction"[Mesh]) OR ("acl reconstruct*")) OR (ACL-R)) OR ("anterior cruciate ligament reconstruct*")) AND (("proprioceptive training" OR "psychological scores" OR "open kinetic chain" OR "closed kinetic chain" OR "return to play" OR "return to sport*" OR "functional performance test*" OR "blood flow restriction training" OR "accelerated rehab*") OR ((postoperative) AND (bracing OR "CPM machine*" OR cryotherapy OR "neuromuscular electrical stimulation" OR "postoperative neuromuscular training" OR "home-based rehab*")))) AND (("Rehabilitation"[Mesh] OR "rehabilitation" [Subheading]) OR (rehabilitat* [tiab]) Filters English, from 2012 - 2020)

**Embase <1974 to 2020 September 22> Search Strategy**:

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1 exp anterior cruciate ligament reconstruction/ or acl reconstruct*.mp. (13523)
2 anterior cruciate ligament reconstruct*.mp. (13473)
3 1 or 2 (15171)
4 proprioceptive training.mp. (294)
5 psychological scores.mp. (264)
6 closed kinetic chain exercise/ or open kinetic chain.mp. or open kinetic chain exercise/ (311)
7 closed kinetic chain.mp. (444)
8 return to sport/ or return to play.mp. (5194)
9 functional performance test*.mp. (281)
10 blood flow restriction training.mp. (102)
11 accelerated rehab*.mp. (412)
12 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 (7007)
13 postoperative.mp. (1032400)
14 (bracing or "CPM machine" or cryotherapy or neuromuscular electrical stimulation or postoperative neuromuscular training or home-based rehab*).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word] (28181)
15 13 and 14 (2716)
16 exp rehabilitation/ or rehabilitat*.mp. (611419)
17 12 or 15 (9678)
18 3 and 16 and 17 (716)
19 limit 18 to (english language and yr="2012 -Current") (518)

**Scopus Search Strategy:** ( TITLE-ABS-KEY ( acl-r OR "acl reconstruct*" OR "anterior cruciate ligament reconstruct*" ) ) AND ( TITLE-ABS-KEY ( rehabilitat* ) ) AND ( ( ( TITLE-ABS-KEY ( "proprioceptive training" OR "psychological scores" OR "open kinetic chain" OR "closed kinetic chain" ) OR TITLE-ABS-KEY ( "return to play" OR "return to sport*" OR "functional performance test*" OR "blood flow restriction training" OR "accelerated rehab*" ) ) ) OR ( ( TITLE-ABS-KEY ( postoperative ) AND TITLE-ABS-KEY ( bracing OR "CPM machine" OR cryotherapy OR "neuromuscular electrical stimulation" OR "postoperative neuromuscular training" OR "home-based rehab*" ) ) ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) AND ( LIMIT-TO ( PUBYEAR , 2020 ) OR LIMIT-TO ( PUBYEAR , 2019 ) OR LIMIT-TO ( PUBYEAR , 2018 ) OR LIMIT-TO ( PUBYEAR , 2017 ) OR LIMIT-TO ( PUBYEAR , 2016 ) OR LIMIT-TO ( PUBYEAR , 2015 ) OR LIMIT-TO ( PUBYEAR , 2014 ) OR LIMIT-TO ( PUBYEAR , 2013 ) OR LIMIT-TO ( PUBYEAR , 2012 ) )

**Web of Science Search Strategy:** TOPIC: (acl-r OR "acl reconstruct*" OR "anterior cruciate ligament reconstruct*") AND (postoperative) AND TOPIC: (bracing OR "CPM machine" OR cryotherapy OR "neuromuscular electrical stimulation" OR "postoperative neuromuscular training" OR "home-based rehab*")OR TOPIC: (bracing OR "CPM machine" OR cryotherapy OR "neuromuscular electrical stimulation" OR "postoperative neuromuscular training" OR "home-based rehab*") AND TOPIC: (rehabilit*) Refined by: PUBLICATION YEARS: ( 2020 OR 2012 OR 2019 OR 2018 OR 2017 OR 2016 OR 2015 OR 2014 OR 2013 ) AND LANGUAGES: ( ENGLISH ) Indexes=SCI-EXPANDED, ESCI Timespan=All years

**Cochrane Database of Systematic Reviews <2005 to September 17, 2020> Search Strategy:**

1 ACL-R.mp. [mp=title, abstract, full text, keywords, caption text] (0)
2 acl reconstruct*.mp. [mp=title, abstract, full text, keywords, caption text] (12)
3 anterior cruciate ligament reconstruct*.mp. [mp=title, abstract, full text, keywords, caption text] (13)
4 1 or 2 or 3 (19)
5 rehab*.ti. or rehab*.ab. (260)
6 proprioceptive training.mp. (4)
7 psychological scores.mp. (3)
8 open kinetic chain.mp. (4)
9 closed kinetic chain.mp. (3)
10 return to play.mp. (0)
11 return to sport*.mp. (20)
12 functional performance test*.mp. [mp=title, abstract, full text, keywords, caption text] (4)
13 blood flow restriction training.mp. [mp=title, short title, abstract, full text, keywords, caption text] (0)
14 accelerated rehab*.mp. [mp=title, short title, abstract, full text, keywords, caption text] (1)
15 postoperative.mp. [mp=title, short title, abstract, full text, keywords, caption text] (1498)
16 bracing.mp. [mp=title, short title, abstract, full text, keywords, caption text] (55)
17 CPM machine.mp. [mp=title, short title, abstract, full text, keywords, caption text] (1)
18 cryotherapy.mp. [mp=title, short title, abstract, full text, keywords, caption text] (163)
19 neuromuscular electrical stimulation.mp. [mp=title, short title, abstract, full text, keywords, caption text] (28)

20 postoperative neuromuscular training.mp. [mp=title, short title, abstract, full text, keywords, caption text] (0)
21 home-based rehab*.mp. [mp=title, short title, abstract, full text, keywords, caption text] (16)
22 16 or 17 or 18 or 19 or 20 or 21 (257)
23 15 and 22 (67)
24 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 23 (97)
25 4 and 5 and 24 (0)

## Appendix II: Summary of Included Studies

### Accelerated Rehabilitation

Christensen et al.[9] prospectively randomized 36 patients who had a primary ACL-R with a 4-strand STG autograft into an accelerated rehabilitation and control group. They evaluated anteroposterior knee laxity, range of motion, and peak isometric force at 12 weeks along with International Knee Documentation Committee (IKDC) scores at 1,12, and 24 weeks postoperatively. Patients in the accelerated rehabilitation group did not wear a postoperative knee brace and began full passive range of motion exercises with emphasis on extension and full weight bearing as tolerated immediately after surgery. Patients in the control group were limited in postoperative weight bearing and wore a brace locked at 20° of extension for the first week; they continued to wear the brace unlocked from 10° - 120° for an additional three weeks before fully supervised full passive range of motion. They were not allowed hyperextension past 0 degrees until six weeks postoperatively. No significant differences were found between either group for knee laxity, range of motion, peak isometric flexion, or subjective IKDC score. These results indicate that an early aggressive postoperative rehabilitation protocol may be equivalent to a nonaggressive rehabilitation after an isolated ACL-R with STG autograft. Notable limitations of this study include lack of blinding and lack of long-term follow-up, as data was only collected up to 24 weeks postoperatively.

Gupta et al.[10] prospectively randomized 40 patients with primary ACL-R with an STG autograft into accelerated and standard rehabilitation groups to evaluate differences in a 6 month follow up. Both groups had the same limits in range of motion, amount of weight bearing, restriction of movement, exercises, and functional activities but each program incorporated these over differing time intervals with the accelerated group incorporating these activities over a 19-week period and the standard group over a 24-week period. Both groups were evaluated at 6 weeks, 3 months, and 6 months postoperatively for anterior laxity and preoperatively, 3 months, and 6 months postoperatively for Knee Osteoarthritis Outcome Score (KOOS). IKDC scores were evaluated at 3 and 6 months postoperatively. Functional testing using a single-leg hop test was assessed preoperatively and at 6 months postoperatively. There were no statistical differences found in anterior laxity between groups ($p > 0.05$). Significant differences were found in IKDC scores between groups at 3 and 6 months after surgery and in the KOOS score at 3 months postoperatively with the accelerated rehabilitation group performing better than the standard rehabilitation group ($p < 0.05$). This indicates that in terms of laxity, patient satisfaction, functional performance, and activity level, an accelerated rehabilitation protocol is equivalent to a standard rehabilitation protocol. In terms of clinical outcomes, the accelerated protocol may be better than the standard protocol when used after an isolated ACL-R with STG autograft.

Feyzioglu et al.[11] prospectively evaluated 15 elite athletes and 15 non-elite athletes in a pre intervention-post intervention study to investigate differences in pain intensity, range of motion, Lysholm scores, and depression after ACL-R with an STG autograft in an accelerated rehabilitation program. This program began two weeks after surgery and lasted for six weeks, but included range of motion and weight-bearing exercises for the initial two weeks. They found significant improvements for pain ($p < 0.05$), knee flexion range ($p < 0.05$), Lysholm score (p <

0.05), and depression ($p < 0.05$) in both elite and non-elite athletes after ACL-R, which suggests that accelerated rehabilitation may be beneficial for both groups. This study was limited by its lack of long-term follow-up, which could serve to further support its clinical relevance.

**Blood Flow Restriction Training**

Hughes et al.[12] randomized twenty-eight participants into two intervention groups to examine the comfort and pain associated with BFR training utilized during postoperative physical therapy; one performed high-intensity resistance training at 70% of 1-repetition maximum (1-RM) and the other performed low-intensity resistance training at 30% of 1-RM with BFR. Both groups attended physical therapy twice weekly for eight weeks following ACL-R and completed unilateral leg press training on both limbs. Borg's (1998) rate of perceived exertion (RPE) and pain scales were used to assess RPE, muscle pain, and knee joint pain following each set of exercise and then averaged to obtain one value for an entire training session. While knee joint pain was lower for the BFR group ($p < 0.05$) both during and 24 hours post-training session, muscle pain was found to be higher ($p < 0.05$) for the BFR group during all sessions. There was no observed difference in RPE ($p > 0.05$) between the groups.

Curran et al.[13] randomized thirty-four patients into four intervention groups: concentric exercise, eccentric exercise, concentric exercise with BFR, and eccentric exercise with BFR to evaluate the efficacy of BFR training combined with high-intensity exercise. Sessions were conducted twice per week for eight weeks beginning ten weeks after ACL-R, and all exercises were performed with resistance at 70% of each patient's 1-RM. Patients in the BFR training groups performed their exercises with a cuff applied to the thigh of the affected leg and inflated to 80% of limb occlusion pressure. Isometric and isokinetic quadriceps peak torque, quadriceps muscle activation, and rectus femoris muscle volume were assessed before ACL-R, after completion of the intervention, and at the time of return to activity. No significant differences were observed between any of the groups for the measured variables at any time point ($p > 0.05$). Based on these observations, using BFR in conjunction with high intensity exercise may not be effective to improve muscular strength and size following ACL-R.

**Bracing**

Dai et al.[14] recruited 23 adolescent patients who were 6-months postoperative following ACL-R to undergo three-dimensional kinematic and kinetic testing while performing a 35° side-cutting task wearing and not wearing a functional knee extension-resistant brace on the surgical extremity. The surgical extremity demonstrated a significant decrease in peak impact vertical ground-reaction force ($p < 0.01$), peak propulsion vertical ground-reaction force ($p < 0.01$), peak knee extension moment ($p < 0.01$), and knee flexion angle at peak knee flexion velocity ($p = 0.01$), peak knee flexion angle ($p < 0.01$), and peak knee flexion velocity ($p < 0.01$) as compared to the nonsurgical extremity during both braced and unbraced conditions. The bracing condition was found to have significantly increased initial knee flexion velocity ($p = 0.01$) and significantly decreased initial knee flexion angle on the surgical extremity ($p < 0.01$). Bracing affected kinematics of the nonsurgical extremity, as well, but did not decrease the asymmetry between the extremities. This is of particular concern with regard to injuring the ACL graft or the contralateral limb with return to sport activities.

Mayr et al.[15] provided four-year follow-up data on a prospective randomized trial that enrolled 64 patients between the ages of 21 and 65 who underwent an arthroscopically assisted ACL-R with an ipsilateral patellar tendon autograft and were either treated with or without a stabilizing knee brace for the first six weeks after surgery. Eighty-one percent of these patients were evaluated at four-years post-op using the IKDC 2000 knee evaluation form, KT1000 measurement for anteroposterior knee laxity, visual analog pain scale (VAS), and radiograph evaluation. No significant differences were observed in IKDC 2000 subjective and objective scores or with KT1000-measured anteroposterior laxity. The braceless group reported significantly better VAS scores for sports activity and heavy physical work ($p = 0.015$), and there were no significant radiographic findings between either group regarding osteoarthritis or tunnel widening. This indicates that postoperative usage of a stabilizing knee brace after ACL-R may not have any advantage over treatment without a brace at 4-year follow-up, and this study recommends against the use of bracing after isolated ACL-R with autologous patellar graft tendon.

Lindström et al.[16] randomized 60 patients who underwent ACL-R with semitendinosus-gracilis tendon grafts into two treatment groups; one group was instructed to wear a light knee brace locked in extension while standing and walking for three weeks after surgery while the other group did not wear a brace during the same postoperative protocol. Both groups were assessed for knee joint effusion using computed tomography (CT), performed the single-leg hop test for distance, and completed patient-reported outcome measures including the Lysholm knee score, Tegner activity scale, and KOOS pre-operatively. All measures were repeated one year after surgery in addition to the triple hop test for distance, the six-meter timed hop test, and the square hop test. Excessive joint effusion was present in 68% of the patients three months after ACL-R and was associated with prior meniscus injury ($p = 0.05$) and higher prior Tegner activity scale ($p = 0.006$). Postoperative bracing was found to have no effect on knee joint effusion. The authors note that a larger clinical cohort would be needed to confirm the findings of their logistic regression.

**Cryotherapy**

Koyonos et al.[18] randomized fifty-nine patients preparing to undergo ACL-R into two groups to investigate the effects of immediate preoperative cryotherapy on postoperative VAS scores and pain medication usage. The intervention group received thirty to ninety minutes of cold therapy on the surgical leg immediately before surgery using a commercial noncompressive cryotherapy unit; the second group received no cryotherapy prior to surgery as a control. Six patients were excluded from the study, resulting in a total of fifty-three patients whose data were included for analysis. In the first thirty-six hours after surgery, the intervention group reported significantly lower pain levels according to the VAS as well as significantly less postoperative narcotic usage than the control group; no other significant differences were noted. The results of this study support the safety and efficacy of preoperative cryotherapy as part of a multimodal pain regimen in populations undergoing ACL-R. Limitations of note include lack of investigator blinding, lack of a placebo interventional group, and failure of the VAS to account for multidimensional characteristics of pain.

Ruffilli et al.[19] randomized forty-seven patients to receive either immediate postoperative cryotherapy via a temperature-controlled cold continuous flow device as an intervention or a standard ice bag as a control group following ACL-R using the "over the top" technique. Postoperative assessments were conducted on the first day after surgery and included subjective pain evaluation using the numeric rating scale (NRS), blood loss from suction drainage, knee circumference at three anatomical landmarks, knee range of motion, painkiller consumption, and a subjective evaluation of the practicality and usefulness of the cold compression device for the intervention group. The intervention group noted significantly lower pain perception, blood loss, knee volume increase, and significantly higher range of motion in the first postoperative day; no significant differences in painkiller consumption were observed. These results provide evidence for usage of a cold compression device to improve immediate postoperative outcomes in patients undergoing ACL-R compared to traditional cold therapy methods. Limitations of the study include lack of blinding, limitation of evaluations to postoperative hospital stay duration, and failure to evaluate the economic impact of the cold compression device.

**Exercise Modalities**

*Closed Kinetic Chain and Open Kinetic Chain Exercise*

Fukuda et al.[20] randomized 49 participants who underwent ACL-R into one of either two groups; one group was assigned an early-start OKC exercise program (EOKC) and the second group was assigned a late-start OKC exercise program (LOKC). The EOKC group began OKC exercise four weeks after surgery within a restricted range of motion, 45° to 90°. The LOKC group performed the same exercise protocol twelve weeks after surgery within a larger range of motion, 0° to 90°. Data measures obtained include quadriceps and hamstring muscle strength, numerical pain rating, Lysholm knee score, single-legged and crossover hop tests, and anterior knee laxity. All data measures were assessed at 12 weeks, 19 weeks, 25 weeks, and 17 months after surgery. Both groups had a higher level of function and less pain at the 19-week, 25-week, and 17-month timepoints compared to 12 weeks after ACL-R ($p < 0.05$). The EOKC group had increased muscular strength at 19 weeks, 25 weeks, and 17 months compared to 12 weeks ($p < 0.05$), whereas the LOKC group did not demonstrate muscular strength improvements until the 17-month follow-up visit. There was no difference observed between groups for all pain and functional assessments ($p > 0.05$). These results suggest that early introduction of OKC exercises into postoperative ACL-R rehabilitation could help patients recover muscular strength faster than late introduction of OKC exercises.

Uçar et al.[21] randomized 58 patients into two groups; one group performed a CKC exercise program while the other performed an OKC exercise program for their postoperative ACL-R rehabilitation. Both groups were assessed preoperatively and at three months and six months postoperatively for the following outcome measures: VAS for subjective pain intensity, active knee flexion, thigh circumference, and Lysholm scores for knee function. No significant differences were observed between the two groups at baseline; however, both groups experienced improved VAS values and knee flexion after surgery. Improvements in VAS values and knee flexion were significantly higher in the CKC group. Increases in thigh circumference difference were observed at both postoperative assessments. Greater improvement in Lysholm scores were observed six months after surgery, indicating that the CKC exercise program was more effective than the OKC exercise program at improving knee function in patients who have undergone ACL-R.

*Plyometric Exercise*
Chmielewski et al.[22] enrolled 24 patients who were, on average, 14 weeks after ACL-R and randomized them into two groups. The groups participated in eight weeks of twice weekly postoperative low- or high-intensity plyometric exercise sessions; groups were distinguished by the expected magnitude of vertical ground-reaction forces. Primary outcomes included self-reported knee function using the IKDC 2000 and a biomarker of articular cartilage degradation. Secondary outcomes included additional biomarkers of articular cartilage metabolism, serum concentrations of the C-terminal propeptide of newly formed type II collagen and inflammation; functional performance as determined by maximal vertical jump and single-legged hop tests; knee impairments including anterior knee laxity, average knee pain intensity, normalized quadriceps strength, and quadriceps symmetry index; and psychosocial status including kinesiophobia, knee activity self-efficacy, and pain catastrophizing. No significant differences were observed between the exercise groups; however, across both groups, improvements were detected in knee function, knee impairments, and psychosocial status. These results support returning to sports following ACL-R, but further investigation would need to be done on the effects of plyometric exercise intensity on articular cartilage biomarkers.

**Functional Testing**
Itherburn et al.[26] examined differences in knee function and strength at time of return-to-sport clearance in a cohort of 124 young athletes who had undergone ACL-R. These athletes were evaluated for KOOS, single-leg hop tests, isokinetic quadriceps and hamstring strength, and limb symmetry during hop tests and strength tests. Participants who successfully resumed their preinjury levels of sports performance were found to demonstrate greater absolute performance in the injured and uninjured limbs on the triple hop test ($p = 0.007$ and $p = 0.004$, respectively) and the crossover hop test ($p = 0.033$ and $p = 0.37$, respectively), and in the injured limb on the single hop test ($p = 0.034$). Measures of limb symmetry did not differ among any groups. The primary implication of this study is that focusing on improvement of absolute, bilateral performance after ACL-R may help promote successful return to sport; however, the observational design of this study may limit any conclusions regarding causation.

Harput et al.[27] evaluated changes in involved and uninvolved quadriceps and hamstring strength and limb symmetry indices (LSI) in a cohort of 38 male participants who had undergone ACL-R six months prior to data collection. Quadriceps and hamstring peak torques for both limbs and LSI were calculated following isometric strength testing of the quadriceps and hamstrings that were performed at one, two, three, and six months after ACL-R. It is typically recommended that quadriceps and hamstring LSI greater than 90% be achieved in order to return to sport; however, in this cohort, only 28.9% of participants achieved > 90% LSI for quadriceps strength, 36.8% achieved > 90% for hamstring strength LSI, and 15.8% of participants achieved LSI of 90% for both quadriceps and hamstring strength at six months postoperatively. These results may not be generalizable to other populations due to the inclusion of only male athletes. Additionally, a lack of longer term follow-up for data measures is severely limiting due to the fact that most current evidence points to delaying return to sport until at least nine months after surgery.[34]

Kline et al.[23] evaluated hip strength in addition to the standard quadriceps and hamstring strength measures that are typically done using hop test performance following ACL-R. A group of 20 patients who had undergone ACL-R were compared to a group of 45 healthy control subjects in this controlled intervention study; participants performed single-leg hops, timed hops, triple hops, and crossover hops to measure peak isometric knee extension, hip abduction, hip extension, and hip external rotation (HER) strength. Knee extension ($p = 0.02$), HER ($p = 0.04$), single-leg hop ($p < 0.01$), triple hop ($p < 0.01$), timed hop ($p < 0.01$), and crossover hop ($p = 0.01$) were significantly impaired in the surgical limb of the ACL-R group compared to the control subject limbs. It was also found that HER was the only measure to significantly predict hop test performance, indicating that clinicians should consider including HER strengthening exercises in their postoperative rehabilitation protocols.

Wellsandt et al.[24] evaluated the uninvolved limb as a reference standard for calculating LSI for return to sport testing and its relationship with ACL reinjury rates. A cohort of 70 athletes underwent quadriceps strength testing and single-legged hop tests before ACL-R and six months after ACL-R. Estimated preinjury capacity (EPIC) levels for each test compared involved limb measures at six months post-op to uninvolved limb measures before ACL-R. It was found that EPIC levels were more sensitive to LSI in prediction of ACL reinjury occurrences, leading the authors to the conclusion that LSI may overestimate knee function after ACL-R and may be related to risk of secondary ACL injury.

Thomeé et al.[25] aimed to describe the variability in leg muscle power and hop performance up to two years after ACL-R to illustrate the effects of various criteria for an acceptable level of muscle function. Eighty-two patients were enrolled in this prognostic prospective cohort study and underwent a battery of lower extremity muscle power tests and three hop tests preoperatively and three, six, twelve, and 24 months after surgery. Only 44% of participants achieved an LSI of ≥ 90% on all three hop tests and only 22% of participants achieved an LSI of ≥ 90% on all six muscle function tests at 24 months post-op. Lowering the LSI threshold to ≥ 80% resulted in 53% of participants achieving criteria on all six tests while increasing it to ≥ 100% was not achieved by any participant. This indicates that more demanding criteria for successful muscle function outcomes using batteries of tests may result in poor outcomes, and should be taken into consideration when presenting ACL-R rehabilitation outcomes or designing rehabilitation protocols.

**Nerve Blocks**

Runner et al.[30] randomized 102 patients undergoing primary ACL-R to receive either an adductor canal block (ACB) or FNB before surgery. After surgery, patients were prompted by a smartphone application to answer various patient-reported outcomes, including when they first regained the ability to perform a straight leg raise. Objective assessments of knee function were performed at three and six months after surgery using isokinetic strength testing. Seventy-three patients' data were analyzed and the mean time to first straight leg raise after surgery was similar for both groups (p = 0.134). Mean extension torque at 60 deg/s increased significantly for both groups (p = 0.008 for ACB and p = 0.006 for FNB) between three and six months post-op, but there was no significant difference in mean extension torque at 60 deg/s or 180 deg/s between the two groups at either postoperative time point. There were also no significant differences in postoperative complications between either group. These results indicate that, with regard to quadriceps strength, there are no statistically or clinically significant differences between administering ACB or FNB for ACL-R. Notable limitations of this study include a lack of placebo intervention and failure to perform any functional testing, such as hop tests.

Okoroha et al.[31] randomized 43 patients undergoing primary ACL-R to receive either a preoperative single-shot FNB (intervention group) or local infiltration anesthesia (control group) for primary pain control, followed by a standardized postoperative rehabilitation protocol. All patients were tested for isokinetic flexion and extension using a Biodex machine and performed three functional tests (single-leg hop for maximum distance, 6-m single-leg hop for fastest time, and single-leg triple crossover hop for distance) at least nine months after surgery. No strength deficit differences were observed in slow isokinetic extension strength (p = 0.51), slow isokinetic flexion strength (p = 0.55), or fast isokinetic flexion strength (p = 0.56). There were no differences in deficits for single-leg hop distance (p = 0.12), timed single-leg hop (p = 0.74), or single-leg triple hop distance (p = 0.94). There was a 13% complication rate in patients who received the FNB; one patient experienced prolonged quadriceps inhibition and two patients experienced prolonged sensory disturbances.

Kurosaka et al.[32] investigated the effectiveness and safety of periarticular injections (PI) versus femoral nerve blocks (FNB) for postoperative pain levels 24 hours after ACL-R by randomizing 129 patients to receive either PI or FNB. Subjective pain levels were assessed using a 100-point VAS score, and patients were also assessed for opioid consumption levels and any postoperative complications. Patients in the PI group reported significantly lower VAS scores ($p < 0.0001$) and opioid consumption (p = 0.0003) than the FNB group 24 hours after surgery. The rate of postoperative complications was not significantly different between groups. This study was not blinded and generalizations made based on its results may not be applicable to regions such as North America and Europe, where ACL-Rs are not typically performed as inpatient procedures.

**Neuromuscular Electrical Stimulation**

Toth et al.[34] assessed the utility of early NMES treatment on preservation of quadriceps muscle fiber size and contractility after ACL injuries and ACL-R. Twenty-one patients were randomized into either a treatment group (NMES) or a sham intervention group (microcurrent electrical nerve stimulation, or MENS) as a control. The NMES group began their intervention within three weeks of their initial injury and continued for three weeks after ACL-R, receiving NMES treatment five days per week for an hour each day. The MENS group underwent sham stimulation with the same treatment frequency but were told that their device administered imperceptible MENS for pain mitigation. Bilateral biopsies of the vastus lateralis were performed three weeks after surgery to assess skeletal muscle fiber size and contractility. Quadriceps muscle size and strength were assessed six months after surgery. The NMES group experienced reduced muscle fiber atrophy ($p < 0.01$) through effects on fast-twitch myosin heavy chain (MHC) II fibers. NMES also preserved contractility in slow-twitch MHC I fibers, which increased maximal contractile velocity ($p < 0.01$) and preserved power output ($p < 0.01$). There were no discernable differences in whole muscle strength between groups at six months after surgery. These results provide cellular-level evidence for the utility of early NMES usage to modify skeletal muscle maladaptations to ACL-R.

Labanca et al.[35] investigated the effects of a six-week NMES treatment protocol superimposed on movement after ACL-R by randomizing 63 patients into three groups. In addition to standard rehabilitation, one group received NMES while performing sit-to-stand-to-sit (STSTS) exercises, the second group performed STSTS exercises without NMES, and the third group received no additional treatment as a control. Participants were tested for maximal voluntary isometric contraction of the knee extensor muscles at 30° and 90° of knee flexion and of the knee flexor muscles at 90° of knee flexion in both extremities. Subjective pain scores were quantified using the VAS, and thigh and knee circumferences were measured from both limbs. Finally, symmetry of lower extremity loading was assessed by recording ground reaction force on two force platforms during a sit-to-stand movement at 15, 30, 60, and 180 days after surgery. Participants in the NMES + STSTS group demonstrated higher strength in the knee extensors as well as lower pain perception and higher symmetry of the lower extremities at 60- and 180-days post-op. The STSTS group demonstrated higher symmetry of the lower extremities than the control group 60 days after surgery. These results provide evidence for supplementation of exercise with NMES to recover quadriceps strength and symmetry in lower extremity loading after ACL-R.

Taradaj et al.[36] investigated the efficacy of NMES usage in male professional soccer players after ACL-R. Eighty participants were randomized into two groups; both groups underwent one month of three-times weekly training sessions after surgery. One group received NMES treatment applied to the quadriceps of both lower extremities three times per day in addition to the training sessions and the second group did not receive NMES treatment. Tensometry, muscle circumference, and the goniometry pendulum test were assessed for all participants at one month and three months after rehabilitation treatment. The comparison of muscular strength between both groups after one month of treatment demonstrated a significant difference in favor of the NMES group ($p = 0.002$). The comparison of quadriceps circumference showed a significant difference in favor of the NMES group as well ($p = 0.04$). No significant differences were observed in terms of the goniometry pendulum test results. This indicates that there are benefits to the usage of NMES in restoring quadriceps strength and mass in male professional soccer players without compromising the biomechanics of the knee joint.

**Patient-Reported Outcome Measures**

Sonesson et al.[38] prospectively evaluated 65 individuals who underwent ACL-R to describe their expectations, motivation level, and satisfaction before surgery and during the rehabilitative process to explore how they may play a role in return to pre-injury level of sport. Swedish translation of the International Knee Documentation Committee Subjective Knee Form (IKDC-SKF) and questions about expectations, satisfaction, and motivation were evaluated preoperatively and at 16-52 weeks postoperatively. This study found that higher motivation during rehabilitation was associated with returning to the preinjury sport activity and that those who returned to their preinjury sport activity were more satisfied with their activity level and knee function one year postoperatively. The authors concluded that motivation is a key factor in return to preinjury sport level.

Paterno et al.[39] prospectively evaluated 40 patients undergoing ACL-R to better understand the relationship between fear, objective measures of functional performance, and second ACL injury after return to sport. A single testing session was done within four weeks of return to sport clearance. The authors found that patients with greater self-reported fear as measured by the Tampa Scale of Kinesiophobia (TSK-11) were four times more likely (OR, 3.73; 95% CI, 0.98-14.23) to have lower levels of activity, seven times more likely (OR, 7.1; 95% CI, 1.5-33.0) to have hop limb symmetry < 95%, six times more likely (OR, 6.0; 95% CI, 1.3-27.8) to have quadriceps strength limb symmetry < 90%, and had an increased risk of secondary ACL injury in the 24 months after return to sport. Particularly, patients who had a TSK-11 of 19 or greater were 13 times more likely (RR, 13.0; 95% CI, 2.1-81.0) to suffer a second tear in this time frame.

Sadeqi et al.[40] prospectively evaluated 681 patients who underwent primary and revision isolated ACL-R to analyze progression of Anterior Cruciate Ligament Return to Sport after Injury (ACL-RSI) score and to identify factors associated with return to preinjury sport level of play. They evaluated patients preoperatively and at four months, six months, one year, and two years postoperatively. The authors found that ACL-RSI scores were significantly higher in patients who returned to their preinjury level of sport with an optimal score at two year follow-up > 65 with a sensitivity of 75.1% and specificity of 68.5%. However, those who returned to sport at the same or higher level had a score of 81.6. Predictive factors of successful return to preinjury sport included an ACL-RSI score greater than 60 at six-month follow up and professional or competitive level of athletic play.

Saha[41] prospectively evaluated 100 patients undergoing ACL-R to evaluate factors associated with return to sport. The author used the IKDC, Tegner activity scale, Lysholm, Marx, and TSK-11 among other measurements preoperatively and at three-, six-, and twelve-month intervals following surgery. No significant difference was noted in IKDC, Lysholm, or Tegner scores between patients who returned to sport and did not return to the same activity level. Notably, 85.5% of patients who returned to sport scored < 15 with a mean score of 14.07 whereas 68.9% of those who did not return to sport scored > 40 with a mean score of 38.46 on TSK-11.

Zwolski et al.[42] aimed to determine whether IKDC-SKF score at time of return to sport was a predictor of quadriceps strength after ACL-R. A cohort of 139 young, athletic patients completed the IKDC and isometric quadriceps strength testing at return to sport. There was a significant correlation between IKDC and peak isometric torque ($p < 0.001$) as well as between IKDC and LSI ($p < 0.001$). An IKDC score ≥ 94.8 predicted quadriceps LSI ≥ 90% with high sensitivity (0.813) and moderate specificity (0.493). This shows that the IKDC may serve as a tool for identifying quadriceps strength deficits in a young, active population; however, it should not be used as a substitute for isokinetic dynamometry.

**Return to Sport/Reinjury Rates**

Webster et al.[46] developed a cohort of 222 patients who underwent ACL-R and were then assessed one year after surgery for sport activity level, knee laxity, limb symmetry, subjective function and symptoms, and psychological readiness. This cohort was then followed out to an average of three years after ACL-R to determine whether they had returned to their self-reported preinjury levels of sport performance. Of these 222 patients, 135 reported that they had returned to their preinjury levels of performance. It was found that higher psychological readiness ($p < 0.0001$), greater limb symmetry ($p < 0.05$), higher subjective knee scores ($p = 0.01$), and a higher activity level ($p < 0.04$) were all factors associated with a return to sport performance. Based on these findings, it was determined that psychological readiness during rehabilitation to return to sport was the most significant predictor of whether an individual would return to their preinjury performance levels.

Nawasreh et al.[47] completed return-to-activity testing on 95 participants six months after undergoing ACL-R. Their battery of tests included isometric quadriceps index, single-legged hop tests, Knee Outcome Survey - Activities of Daily Living Scale (KOS - ADLS), and Global Rating Scale (GRS). Participants were then put into one of two groups depending on their testing scores; those that achieved a score of ≥ 90% on all criteria were put into the PASS group while those who scored < 90% were put into the FAIL group. All participants were asked at 12 and 24 months postoperatively whether they had returned to their preinjury levels of sport participation. Eighty-one percent and 84.4% of the PASS group had reported return to their preinjury activity level while only 44.2% and 46.4% of the FAIL group returned at 12- and 24-months post-op, respectively. The 6-meter timed hop, single hop, and triple hop limb symmetry indexes; KOS - ADLS; and GRS individually predicted return to activity at one year after surgery ($p \leq 0.024$) while all hop tests individually predicted to return to activity at two years after surgery ($p \leq 0.007$).

Arundale et al.[48] secondarily analyzed prospectively collected data on 117 female athletes after a primary ACL-R to evaluate duration of rehabilitation and its effect on tuck jump and drop vertical jump. The study found no difference in tuck jump score or probability of high peak knee abduction moment during drop vertical jump landing based on rehab duration. The main implication of this study was that time alone cannot be used to determine return to sport and that more objective criteria should be used instead.

Grindem et al.[49] prospectively enrolled 106 athletes involved in pivoting sports to participate in a two-year cohort study. Sports participation and knee reinjury rates were assessed monthly following ACL-R while KOS - ADLS, GRS, quadriceps strength, and hop test symmetry were evaluated before surgery as well as at six and twelve months after surgery. Members of the cohort were considered to pass their functional criteria if they achieved > 90% on all tests or they were considered to fail if they failed to achieve 90% on any of the tests. Participants who returned to level I sports had a 4.32 ($p = 0.048$) times higher rate of reinjury than those who did not, and rate of reinjury was significantly reduced by 51% for each month that return to sport was delayed until nine months post-op, at which no further reduction of risk was observed. 38.2% of those who did not achieve 90% on all return to sport criteria experienced reinjuries while only 5.6% of those who passed return to sport criteria reinjured their surgical limbs. It was found that more symmetrical quadriceps strength significantly reduced the rate of reinjury.

http://dx.doi.org/10.2106/JBJS.21.00688


Arundale et al.[50] examined reinjury rates as a function of return to sport time in men enrolled in a secondary ACL injury prevention program including progressive strengthening, agility training, and plyometrics as part of the ACL-SPORTS trial. Forty males who participate in cutting and pivoting sports were evaluated for return to sport testing and in follow-up sessions at one and two years after ACL-R. At one year after ACL-R, 95% of participants had returned to sport with 78% reporting they had reached preinjury levels of activity. At two years after ACL-R, all participants had returned to sport with 95% reaching preinjury activity levels and only one athlete suffering a second ACL injury. These return to sport and reinjury rates are much higher than those reported in literature, indicating that the secondary ACL injury prevention program may be beneficial for those athletes wishing to return to preinjury levels of activity.

Angelozzi et al.[51] enrolled 45 male professional soccer players into a cohort in order to investigate the rate of force development (RFD) to 30%, 50%, and 90% of maximal voluntary isometric contraction (MVIC) as an adjunct outcome measure to determine readiness to return to sport following ACL-R. These measures were taken preinjury as part of a standard preseason assessment as well as six and twelve months after ACL-R. While the average MVIC value at six months post-op was 97% of that achieved preinjury, the 30% RFD, 50% RFD, and 90% RFD values were 80% ($p = 0.04$), 77% ($p= 0.03$), and 63% ($p = 0.007$) of their preinjury values, respectively. The mean RFD values reached or exceeded 90% at the 12-month postoperative time points, following a rehabilitation program focused on muscular power. This suggests that after ACL-R, utilization of RFD criteria may be a useful adjunct outcome measure to aid in decision making for athletes returning to sport.

Beischer et al.[43] investigated the association between reinjuring a surgically reconstructed ACL and time to return to sport, symmetrical muscle function, and symmetrical quadriceps strength at time of return to sport in a cohort of 159 athletes. Athletes who had a higher preinjury Tegner Activity Scale score ($p < 0.01$) and athletes who returned to knee-strenuous sport before nine months postoperatively ($p < 0.001$) had a higher rate of sustaining a second ACL injury. No association was found between symmetrical muscle function or quadriceps strength and secondary ACL injury. This provides evidence against athletes returning to strenuous sport activity before nine months postoperatively.

**Sensorimotor Training**

*Electromyography Biofeedback Training*

Christanell[53] investigated how EMG biofeedback (EMG BFB) therapy affected knee extension and strength after ACL-R. Electromyography biofeedback therapy uses electrodes placed on a patient's muscles to generate either an auditory or visual feedback signal as a response to muscle activation.[64] For this particular study, sixteen patients were randomized into two groups. The control group underwent a standard rehabilitative protocol that consisted of full postoperative weight bearing, knee bracing, electrical stimulation, aquatics, and proprioceptive training. The treatment group underwent the same protocol with the addition of EMG BFB therapy in addition to lower extremity exercises for the first six weeks after surgery. The High-Heel-Distance (HHD) test, range of motion, and integrated EMG (iEMG) for vastus medialis were measured one week before surgery and one, two, four, and six weeks after surgery. Knee function, swelling, and pain were also assessed using standardized scoring scales. Passive knee extension ($p < 0.002$) and the HHD test ($p < 0.01$) were significantly better in the EMG BFB group compared to the control group at six weeks post-op. The EMG BFB also demonstrated significant increases in iEMG at two weeks ($p < 0.01$) and six weeks ($p < 0.01$) post-op. No significant ($p > 0.01$) differences were observed in knee function, pain, or swelling at any time. These results indicate that early EMG BFB therapy for ACL-R rehabilitation can be useful in improving knee extension due to improved innervation of the vastus medialis. Notable limitations of this study include relatively small sample size, lack of blinding of investigators, and failure to use a separate treating and measuring therapist.

*Perturbation Training*

Takahashi et al.[55] developed a CKC exercise rehabilitation protocol supplemented with balance training with a shaking board while low-frequency electrical stimulation was applied to the quadriceps muscles. Twenty participants were randomized into either a group that underwent the supplemented rehabilitation protocol or a group that underwent traditional rehabilitation after ACL-R. An isokinetic dynamometer was used to measure muscular strength of both the affected and unaffected extremities and muscle mass was evaluated using computed tomography (CT) imaging. Measurements were performed once before beginning rehabilitation and once per month for three months after beginning either protocol for a total of four measurements. Muscular strength of the injured limb showed a significant improvement in the balance training group compared to the traditional rehabilitation group ($p < 0.01$) after one month of rehabilitation. The cross-sectional area of the extensor muscles of the injured limbs of the balance training group showed a greater increase after three months of rehabilitation than the traditional rehabilitation group. Results of this study indicate that the supplemental balance training facilitated contraction of fast-twitch muscles, which could be responsible for greater extensor muscle strength improvement after ACL-R.

Arundale et al.[56,57] and Capin et al.[58] completed primary and secondary analyses of their ACL-SPORTS trial in which 79 athletes were randomized into one of two different secondary ACL injury prevention programs. One program consisted of progressive strengthening, agility training, and plyometrics (SAP), and the second program consisted of the same three elements plus perturbation training (SAP + PERT). Numerous outcomes were assessed one and two years after ACL-R, including but not limited to gait analysis, quadriceps strength, single-leg hop testing, IKDC scores, and KOOS scores.

Arundale et al.[56] completed a secondary analysis of all 79 athletes enrolled in the ACL-SPORTS trial in order to investigate whether the secondary injury prevention programs had any effect on quadriceps strength limb symmetry, single-leg hop test limb symmetry, and patient-reported knee outcome scores between both the SAP and SAP + PERT groups as well as between men and women. No differences were observed for any variables between the SAP and SAP + PERT groups; however, there were significant increases made in all variables except quadriceps strength limb symmetry. Men and women made significant increases in all knee function and patient-reported outcome measures except quadriceps strength limb symmetry, in which men made significant improvements but women did not. These results suggest that while the secondary injury prevention program may be a beneficial addition to traditional ACL-R rehabilitation, women may need further quadriceps strengthening to maintain and improve quadriceps symmetry between limbs.

Arundale et al.[57] conducted follow up analyses on the male athletes enrolled in the ACL-SPORTS trial to determine if the secondary injury prevention programs had any effect on quadriceps strength, single-legged hop test limb symmetry, patient-reported knee outcome scores, and time to return to sport after ACL-R. Forty men from the original trial met enrollment criteria and were assessed for these outcomes at one and two years after surgery. No significant differences were observed between the SAP and SAP + PERT groups for quadriceps symmetry ($p = 0.45$), single-legged hop test symmetry, patient-reported outcome measures, or time to pass return to sport criteria ($p = 0.09$). These results indicate that the addition of perturbation training to a secondary injury prevention program of strengthening, agility, and plyometrics may not contribute any additional benefits to the training program.

Capin et al.[58] performed gait mechanics analyses of the same sub-cohort of men enrolled in the ACL-SPORTS trial to investigate whether the secondary injury prevention programs had an impact on gait symmetry at one or two years after ACL-R. Motion analysis was conducted on the forty males enrolled in this trial to assess sagittal and frontal plane hip and knee angles and moments at peak knee flexion angle; sagittal plane hip and knee angles and moments at peak knee extension angle; sagittal plane hip and knee excursion during weight acceptance; and sagittal plane hip and knee excursion during midstance. There were no differences between the SAP and SAP + PERT groups for any of the biomechanical gait variables or with regard to eliminating gait asymmetries, which persisted in both groups to a large degree at both postoperative time points. This indicates that the secondary injury prevention training programs alone do not serve to eliminate gait asymmetry and perhaps additional interventions would be required.

Fu et al.[54] investigated the effect of whole-body vibration therapy (WBVT) on neuromuscular control after single-bundle ACL-R. Forty-eight patients were randomized to receive either conventional postoperative rehabilitation or eight weeks of WBVT in addition to the conventional rehabilitation starting one month after surgery. Joint position sense, postural control, knee isokinetic performance, range of motion, joint stability, and functional ability were assessed preoperatively and at one, three, and six months postoperatively. The group that received WBVT exhibited significantly better postural control, muscle performance, single-legged hop test performance, and shuttle run performance ($p < 0.05$) than the conventional rehabilitation group, but there was no significant difference observed in knee joint position sense, triple hop test performance, carioca performance, range of motion, or stability ($p > 0.05$). These results provide quantitative evidence in support of WBVT to improve postural control, isokinetic performance, single-legged hop, and shuttle run without compromising knee range of motion or joint stability. This study did not conduct any assessments related to patient-reported outcome measures.

**Supervised Rehabilitation**

Przybylak et al.[59] performed a controlled intervention study investigating the effects of supervised versus non-supervised postoperative physical therapy on return to sport activity levels and quality of life in athletes undergoing ACL-R. Fifty patients were placed into either a group that underwent supervised physical therapy visits after their ACL-R or a group that was given a list of exercises to perform on their own at home after surgery, only meeting with the physical therapist once at every stage to receive new exercises. Patients were evaluated preoperatively and 12 months postoperatively using the Kujala Scale, Tegner Scale, KOOS, the Functional Movement Screen (FMS), and range of motion. Both groups demonstrated higher levels of functional and sports activity and had a better quality of life 12 months after ACL-R. Patients in the supervised group returned to a significantly higher level of sports activity according to the Tegner Scale ($p = 0.003$) and reported significantly better quality of life 12 months after ACL-R according to the KOOS Quality of Life section ($p < 0.001$). Notable weaknesses of this study include a lack of randomization and power analysis.

Nyland et al.[60] enrolled one hundred fifty athletically active teenagers and adults into a supervised return to sports bridge program after their standard postoperative ACL-R physical therapy was completed. The bridge program consisted of whole-body neuromuscular control, progressive resistance strength training, and agility training. Participants attended one session weekly with a licensed physical therapist and a licensed athletic trainer with strength and conditioning specialist certification. Knee laxity and perceived function were assessed prior to program enrollment using maximum anterior translation and pivot shift testing and the Knee Outcome Survey Sports Activity Scale (KOS SAS), respectively. Functional movement form, dynamic knee stability, lower extremity power, agility, and sports skills were assessed after completion of the bridge program. Most subjects (84%) returned back to sports at or above their pre-injury performance skill or level, and within 2 to 13 years after surgery, only ten participants had reported sustaining an ipsilateral knee re-injury or contralateral knee injury (rates of 1.3% and 2.7%, respectively). The authors suggest that their observed results indicate that supplementing standard rehabilitation with a supervised return to sports bridge program can improve patient outcomes and decrease ipsilateral knee re-injury and contralateral knee injury rates.