A Systematic Review of Anterior Cruciate Ligament Reconstruction Rehabilitation

Part II : Open Versus Closed Kinetic Chain Exercises, Neuromuscular Electrical Stimulation, Accelerated Rehabilitation, and Miscellaneous Topics

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ABSTRACT: Anterior cruciate ligament (ACL) reconstruction is a common surgical knee procedure that requires intensive postoperative rehabilitation by the patient. A variety of randomized controlled trials have investigated aspects of ACL reconstruction rehabilitation. A systematic review of English language level 1 and 2 studies identified 54 appropriate randomized controlled trials of ACL rehabilitation. This part of the article discusses open versus closed kinetic chain exercises, neuromuscular electrical stimulation, accelerated rehabilitation, and miscellaneous topics.

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INTRODUCTION

Anterior cruciate ligament (ACL) reconstruction is a common procedure to allow patients to return to their former active lifestyle. Rehabilitation of the reconstructed knee is critical for the successful return to risky cutting and jumping activities. Although many of the individual aspects of ACL rehabilitation have been evaluated using randomized trials, few reviews have used an evidence-based approach to create an overall protocol for ACL rehabilitation. Previous systematic reviews were not inclusive of all possible aspects of rehabilitation (ie, bracing) and did not encompass many recently published studies.[19,22,23,30]

The goal of this systematic review is to assemble the available randomized controlled trials in ACL rehabilitation to facilitate the development of evidence-based rehabilitation protocols. This article represents the second in a 2-part systematic review.

METHODS

PubMed 1966-2005, Embase 1980-2005, and the Cochrane Controlled Trials Register were searched for ar-

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ticles appropriate to this study. Bibliographies of identified studies also were searched, and a hand review of the past 6 months of appropriate journals was performed. For the database search, terms included anterior cruciate ligament, ACL, rehabilitation, randomized trials, and clinical trials. This search identified 82 potential studies for inclusion. Inclusion criteria included English-language randomized clinical trials involving ACL reconstruction rehabilitation. Exclusion criteria included non-English language, no true randomization, and subject matter not pertaining to ACL reconstruction rehabilitation. This resulted in 54 studies included in this systematic review. Studies underwent worksheet appraisal for methodologic quality with emphasis on identifying biases present in each study. All studies were level 1 or 2 evidence. Topics included in this review are continuous passive motion (CPM), rehabilitative bracing, neuromuscular electrical stimulation, early weight bearing, home versus supervised physical therapy, open versus closed chain kinetic exercise programs, and accelerated rehabilitation, as well as a variety of miscellaneous topics assessed by only 1 randomized trial.

OPEN VERSUS CLOSED KINETIC CHAIN EXERCISES

Despite the significant amount of discussion that has occurred regarding the merits of open and closed kinetic chain exercises, only 5 prospectively randomized studies[4,13,17-19] following ACL reconstruction have been conducted to investigate these issues. The first study, by Bynum et al[4] in 1995, evaluated rehabilitation following bone-patellar tendon-bone autograft ACL reconstruction using open versus closed chain exercises for a 24-week course. One hundred patients were prospectively randomized using a computer-generated number and envelope system. Examiners were blinded and performed examinations at 3-month intervals and annually. Three patients dropped out prior to completing the 24-week course, leaving 47 in the open chain group and 50 in the closed chain group. Parameters assessed included Lysholm and Tegner scores, patient satisfaction, range of motion, patellofemoral pain, and KT-1000 instrumented laxity. Sixty-six percent returned for objective and subjective final follow-up. An additional 22% underwent follow-up subjectively (88%). Final follow-up occurred on average at 19 months (range, 12-36 months).

A statistically significant difference was noted in KT-1000 maximum values at final follow-up. Mean maximum value was 1.6 mm for the closed chain group and 3.3 mm for the open chain group ($P = .02$). At the 9-month evaluation, patellofemoral pain was noted in 15% of the closed chain group versus 38% in the open chain group ($P = .046$). Subjective patient assessment and Lysholm and Tegner scores were equivalent in both groups. Twenty-one patients in the closed chain group thought they returned to normal activities of daily living sooner than expected versus 10 in the open chain group ($P = .007$). The authors concluded closed chain exercises were safe and effective, and might offer the advantages of less stress on the healing graft and less patellofemoral pain.

Mikkelsen et al,[17] in a 2000 study, appraised the addition of open chain exercises at 6 weeks to a closed chain rehabilitation program. Forty-four patients were randomized to either a closed chain rehabilitation program for the entire rehabilitation period or to a closed chain program that had the addition of open chain exercises 6 weeks postoperatively. At 6 weeks, the open chain group added isokinetic concentric and eccentric quadriceps strengthening between 90° and 40°, increasing over 6 weeks to 90° to 10°. The other group continued closed chain exercises for the entire 12 weeks. Randomization, blinding, or independent assessors were not discussed. Surgical technique was endoscopic bone-patellar tendon-bone autograft.

Parameters assessed included instrumented laxity (KT-1000 manual maximum), isokinetic strength testing, and patient satisfaction. KT-1000 values showed no significant difference in knee laxity at 6 months. The authors reported a significant increase in quadriceps strength in the open chain group at 6 months, but no statistics were cited. Patient satisfaction evaluation at an average of 31 months demonstrated subjectively that a higher rate of patients in the open chain group returned to sports at the same level than in the closed chain group ($P < .05$). The authors concluded open chain exercises could be safely added at 6 weeks postoperatively without risk of increased knee laxity and with the added potential of improved quadriceps strength and better return to sports.

The next 3 studies[13,18,19] involved the same cohort of patients, although different numbers were involved in each trial. Each trial assessed different parameters but only after 6 weeks of rehabilitation. Patients were entered into the studies after 2 weeks of standard physical therapy. Thus, the authors evaluated the effect of 4 weeks of open chain versus closed chain exercises with no further follow-up.

The first study, published by Morrissey et al[19] in 2000, evaluated the effect of open chain exercises on instrumented knee laxity. Thirty-six patients were randomized to 1 of 2 groups. The closed chain group performed predominantly leg press exercises between weeks 3 and 6 following ACL reconstruction. The open chain group performed knee and hip extensor exercises using either ankle weights or machines. Randomization was performed using the block method. Observers blinded to patient allocation were used for assessment. A power analysis was performed prior to the study, indicating 60 patients were required. The reasons why only 36 patients were recruited were not addressed in the article.

The Knee Signature System was used to determine instrumented laxity at 2 and 6 weeks. The open chain group was determined to be 9% looser, but the 95% confidence interval ranged from −8% to +29%. Thus, the authors could not conclude open chain exercises increased knee laxity.

Hooper et al,[13] in a 2001 study, evaluated the effect of open chain exercises using gait analysis on level walking, stair ascent, and stair descent. Once again, the open chain group performed these exercises between weeks 3 and 6, whereas the closed chain group performed leg presses between weeks 3 and 6.

A Hughston clinical score visual analog scale was used at 2 and 6 weeks and was equivalent between both groups. Gait analysis demonstrated level walking was equivalent in both groups at both time points. The only difference between the 2 groups was a decreased knee angle at stair ascent in the closed chain group ($P < .05$). The authors admitted this was of questionable clinical significance. Walking gait analysis and stair ascent and descent analysis improved significantly in both groups between 2 and 6 weeks.

Morrissey et al,[18] in a 2002 study, evaluated open versus closed chain exercises as discussed in the previous 2 studies and their effect on postoperative pain. Isometric and isokinetic testing was performed at 2 and 6 weeks, and 3 questions from the Hughston clinical score were assessed, including 1 question regarding pain with sitting. The authors believed this addressed patellofemoral pain. Isometric and isokinetic testing was equivalent in both groups, and there was no difference in the pain scores.

These studies demonstrate the need for additional research in this area. Bynum et al[4] found increased knee laxity in the open chain group, but no determination can be made regarding which exercises may contribute to this laxity. Open chain exercises initiated 6 weeks postoperatively, as in the study by Mikkelsen et al,[17] may be safe and improve patient outcome. The other 3 studies assessed final outcome at 6 weeks following 4 weeks of open chain versus closed chain exercises, and this follow-up may be too short to make reasonable conclusions.[13,18,19] Also, these 3 studies may suffer from lack of power to detect a difference.

NEUROMUSCULAR ELECTRICAL STIMULATION

Fourteen randomized controlled trials* have evaluated the use of electrical stimulation during the course of postoperative ACL reconstruction rehabilitation. In 1979, Eriksson and Haggmark[11] conducted a study of 8 patients undergoing ACL reconstruction using a modified Jones procedure. All 8 patients were casted and underwent isometric training. Four of the 8 patients also had percutaneous electrical stimulation that was used to train for 1 hour 5 days per week during the 4 weeks after the first postoperative week. Randomization was not addressed. The electrical stimulation group noted less muscle atrophy and increased succinate dehydrogenase activity, compared with the cast and isometric training only group.

1, 7, 9, 11, 12, 14, 21, 22, 24, 26-29, 33.

Arvidsson et al,[1] in a 1986 study, evaluated the effect of electrical stimulation during cast immobilization following ACL reconstruction. Thirty-eight patients were randomized following ACL reconstruction using the medial one-third of the patellar tendon; randomization was not discussed. All patients were splinted for 1 week and then casted for 5 weeks at 45° of flexion. All patients performed isometric quadriceps sets in the cast. Patients randomized to electrical stimulation underwent 30-minute sessions 3 times daily for the first 6 weeks (40 Hz, pulse width 300 microseconds, 20-second duration with a 35-second rest).

Parameters assessed included computed tomography (CT) preoperatively and 40 to 45 days postoperatively, muscle biopsy for histology and muscle enzymes. Hamstring cross-sectional area decreased significantly in men in the electrical stimulation group ($P < .05$). In women, a significant difference was noted in quadriceps cross-sectional area, which was decreased 31.4% in the control group and 15.6% in the electrical stimulation group ($P < .001$). On biopsy, muscle fiber area minimally decreased in women (5.4%) in the electrically stimulated group. In women in the control group and in all men, a 30% to 40% decrease in muscle fiber area was noted. The authors concluded electrical stimulation decreased the amount of muscle wasting, especially in women. They could not explain the differences observed by gender.

Sisk et al,[26] in a 1987 study, examined the effect of electrical stimulation in casted patients on isometric quadriceps strength. Twenty-two patients were randomized to a cast for 4 weeks at 45° and then a casted brace for 2 weeks with range motion of 45° to 90° with or without the addition of electrical stimulation (frequency 40 Hz, duration 300 microseconds, on 10 seconds and off 30 seconds for 8 hours per day). Randomization method or use of an independent observer were not addressed in the article. Isometric quadriceps strength was evaluated 7, 8, and 9 weeks postoperatively. No difference was noted in quadriceps strength between the 2 groups.

Wigerstad-Lossing et al,[33] in a 1988 study, evaluated the effect of electrical stimulation in addition to voluntary muscle contraction. Twenty-six patients were randomized following ACL reconstruction using the medial one-third of the patellar tendon. Both groups had a full-length cast for 3 weeks at 20° to 30° of flexion followed by 3 weeks in a knee cast. The experimental group underwent electrical stimulation with pulse width 300 microseconds with a 2-second rise, followed by a 6-second stimulation, followed by a 10-second pause for 10 minutes 4 times per day, 3 days per week. Randomization, blinding, and independent assessment were not addressed. Three patients in the control group were excluded for compliance issues. Isometric muscle strength preoperatively and at 6 weeks postoperatively along with CT and muscle biopsy was performed.

Isometric muscle strength decreased significantly in the control group (58% versus 39%, $P < .01$). Computed tomography cross-sectional area decreased less in the electrical stimulation group (23% versus 29%, $P < .05$). Type I muscle fiber area in the control group decreased significantly ($P < .025$).

Delitto et al,[7] in a 1988 study, evaluated the addition of electrical stimulation co-contraction to voluntary isometric co-contractions following ACL reconstruction. Twenty patients were randomized to either voluntary exercise or electrical stimulation trials 5 days per week for 3 weeks during the first 6 postoperative weeks. Randomization was not discussed, but assessment was performed by a blinded observer. Patients were evaluated by isometric testing at the 6-week postoperative point. Electrical stimulation parameters included a 2500-Hz carrier wave, 50 pulses per second increased to the patient's tolerance, 15 seconds on with a 50-second rest period. The amounts and number of repetitions were not discussed in this group. Isometric torque was significantly increased in the extensors and flexors in the electrical stimulation group ($P < .05$).

In a 1991 study, Snyder-Mackler et al[29] evaluated 10 patients randomized to electrical stimulation during co-contraction versus co-contraction alone 3 times per week for the third through sixth weeks of rehabilitation. Randomization and blinding were not discussed. Compliance was assessed by home exercise logs. There were no missed treatments in either group. Electrical stimulation delivered a 2500-Hz (pulse width, 400 microseconds) triangular, alternating current at a 50% duty cycle of 75 bursts per second.

Gait, isokinetic testing, and KT-1000 instrumented laxity were used to assess outcome. Gait was determined to be better in the electrical stimulation group. KT-1000 testing was not significantly different in either group. Isokinetic testing was improved in the electrical stimulation group, with peak torque normalized 69% versus 44% in the control group ($P < .05$).

Draper and Ballard,[9] in a 1991 study, evaluated the effect of electrical stimulation versus electromyographic (EMG) biofeedback on quadriceps strength following ACL reconstruction. Thirty patients were randomized. Randomization was by a matching procedure controlling for age and gender. Compliance was assessed using log sheets. Fifteen patients used electrical stimulation in conjunction with their home exercise program for the first 4 weeks postoperatively for 30 minutes 3 times per day. Electrical stimulation settings included amplitude 50 mA and 35 pulses per second. The second group used EMG biofeedback in addition to the home exercise program to help achieve a voluntary maximum contraction. Isometric Cybex testing was performed 6 weeks postoperatively. The biofeedback group demonstrated improved recovery of quadriceps strength, compared with the nonoperative limb (46.4%) versus electrical stimulation (37.9%) ($P = .044$).

Snyder-Mackler et al,[27] in a 1995 study, evaluated the effect of high-intensity electrical stimulation versus low-intensity electrical stimulation and high-level volitional exercises. One hundred ten patients were randomized to 4 groups in a multicenter study using all types of ACL reconstruction. Randomization was performed centrally, but the method was not discussed. Thirty-one patients were randomized to high-intensity neuromuscular electrical stimulation with a 2500-Hz triangular alternating current at 75 bursts per second for 15 contractions with 11 seconds on and 120 seconds off 3 times per week. The second group of 34 patients underwent high-level volitional exercises. The third group of 25 patients performed low-intensity neuromuscular electrical stimulation with a duration of 300 microseconds at 55 pulses per second, 15 seconds on and 15 seconds off for 15 minutes, 4 times per day, 5 days per week. Twenty patients in the fourth group combined the high-intensity and low-intensity neuromuscular electrical stimulation.

Gait and isometric strength were evaluated 4 weeks after initiating their treatment group. Gait and strength data were analyzed by an observer blinded to group allocation. High-intensity electrical stimulation either alone or in combination with low-intensity electrical stimulation demonstrated increased recovery of the opposite limb quadriceps strength (70% versus 51% for the low-intensity alone group, versus 57% for the volitional group) ($P = .001$). Gait analysis demonstrated increased flexion-extension excursion with a more normalized gait in the high-intensity group. Patellar tendon autografts scored lower than other groups (allografts or hamstring) ($P < .05$). In a separate article published in 1994, Snyder-Mackler et al[28] used the high-intensity and low-intensity groups from the previous study[29] and published these data separately with similar conclusions.

Lieber et al,[14] in a 1996 study, evaluated electrical stimulation and a matched intensity volitional exercise program. Forty patients were randomized to 2 groups. The randomization method was not addressed. The first group used an electrical stimulator with an asymmetrical bipolar charged balance signal with maximum amplitude of 100 mA with a frequency of 50 and a stimulation pulse width of 250 microseconds. The second group performed volitional contractions matched to the intensity of the electrical stimulation with 15% of the injured leg's maximum voluntary contraction for the first week, 25% for the second week, 35% for the third week, and 45% for the fourth week 30 minutes per day, 5 days per week for 4 weeks. The 2 groups were evaluated using maximum voluntary contraction. There was no difference between the groups at 6, 8, 12, 24, and 52 weeks following surgery.

Paternostro-Sluga et al,[21] in a 1999 study, evaluated 49 patients undergoing ACL repair or reconstruction. Patients were randomized to 3 groups: group 1 performed neuromuscular electrical stimulation, 1 set at 30 Hz and 1 set at 50 Hz, 0.2 microseconds, 1 time per day, 7 days per week; group 2 used transcutaneous stimulation for analgesia and performed a home exercise program; group 3 performed exercises alone. Randomization method was not addressed, but the study was double blinded with regards to stimulation type. Isokinetic and isometric strength was tested at 6, 12, and 52 weeks postoperatively. There were no significant differences in either group at any time point.

In a 2000 study, Ross[24] evaluated the effect of neuromuscular electrical stimulation in conjunction with closed kinetic chain exercises following patellar tendon autograft ACL reconstruction. Twenty patients were randomized using a posttest randomization design to 2 groups. No blinding or independent assessment was used. Group 1 performed closed kinetic chain exercises as part of their rehabilitation protocol. Group 2 performed an identical rehabilitation protocol, with the addition of neuromuscular electrical stimulation during the closed kinetic chain exercise portion. The neuromuscular unit was a symmetrical biphasic square wave programmed at a frequency of 50 pulses per second with a 200-microsecond phase duration. Each contraction lasted 15 seconds, including a 3-second ramp on followed by a 35-second rest period.

Results were assessed using KT-1000 testing, unilateral squat test, lateral step up test, and anterior reach test at 6 weeks postoperatively. The neuromuscular electrical stimulation group obtained an additional 6.07° of flexion during the unilateral squat test and 3.3 additional repetitions during the lateral step up test. These differences were statistically significant ($P \leqslant .05$). KT-1000 instrumented laxity and the anterior reach test did not demonstrate a difference between the 2 groups. The author concluded the addition of neuromuscular electrical stimulation to closed kinetic chain exercises resulted in better lower extremity performance.

Rebai et al,[22] in a 2002 study, evaluated 10 patients randomized to electrical stimulation with 80 Hz versus 20 Hz following ACL reconstruction. The 20-Hz group had a pulse width of 300 microseconds with 15 seconds on and 10 seconds off for 60 minutes. The 80-Hz group had a pulse width of 300 microseconds with 15 seconds on and 75 seconds off for 54 minutes. This was performed 5 days per week for 12 weeks in addition to a standardized rehabilitation program. Randomization, blinding, and independent assessment were not addressed in the study.

Isokinetic strength and muscle and fat volumes by magnetic resonance imaging (MRI) were evaluated 12 weeks postoperatively. The 20-Hz group recovered strength better compared with the contralateral limb but did not recover better compared with the ipsilateral limb preoperatively. Thus, there were no significant strength differences between the 2 groups. There was less fat accumulation in the 20-Hz group (10% versus 20%, $P < .05$). Muscle volumes were equal in both groups.

Fitzgerald et al,[12] in a 2003 study, evaluated neuromuscular electrical stimulation in conjunction with rehabilitation. Forty-eight patients were randomly assigned to either the electrical stimulation group or the control group. Five patients dropped out prior to final data analysis. Randomization method, blinding, and independent observation were not addressed in the study. The difference in this study was that electrical stimulation was performed with the knee in full extension. Amplitude was used such that a full tetanic contraction was elicited and increased as tolerated with a 2500-Hz alternating current 75 bursts per second, 2 times per week for 12 weeks.

Outcome was assessed by evaluating isokinetic quadriceps strength at 12 and 16 weeks postoperatively, knee outcome survey regarding activities of daily living, and a 0 to 10 knee pain rating. The electrical stimulation group demonstrated better quadriceps strength at 12 weeks ($P < .05$). The time to begin agility training was better in the electrical stimulation group. Reaching functional parameters to begin crutch and treadmill training was equal in both groups. Activities of daily living score was increased in the electrical stimulation group. Knee pain ratings were equal in both groups.

Because of the variety of parameters used in these studies, it is difficult to make generalized conclusions regarding the use of neuromuscular electrical stimulation following ACL reconstruction. The quality of the studies varied, but in general, most of the studies did not address randomization, were not blinded, and did not use independent observers to assess the results. Many of the early studies evaluated the use of electrical stimulation in casted patients, which currently is rarely performed. Although some studies demonstrated improved isokinetic strength, this was not correlated with patient-based outcome measures or other functional testing. In addition, patient satisfaction with the treatment was rarely assessed.

Despite these shortcomings, some general conclusions can be made. It appears that for neuromuscular electrical stimulation to be successful, it must be applied in a high-intensity setting early in the postoperative period. High-intensity stimulation typically is administered in an outpatient physical therapy setting, thus precluding home units. This is borne out by the studies in this series. Neuromuscular electrical stimulation may help achieve improved quadriceps strength but does not appear to be a requirement for successful ACL reconstruction rehabilitation.

ACCELERATED REHABILITATION

Based on anecdotal success, ACL rehabilitation protocols slowly evolved from a 12-month time frame to a generally accepted 6-month time frame for return to sports. Some orthopedists advocate even shorter rehabilitation protocols. Evidence for these shorter intervals will be helpful for orthopedists to justify decisions regarding return to sports. Minimal current evidence exists in this area regarding safe time intervals for return to sports. Two randomized controlled trials have been published to evaluate the effects of accelerated ACL reconstruction rehabilitation.

Ekstrand,[10] in a 1990 study, randomized 20 soccer players to 2 different rehabilitation protocols, with the goal of returning to sports at 6 months versus 8 months following ACL reconstruction using an autologous fascia lata graft. Randomization method, power study, or confidence intervals for outcome measures were not presented. All of the patients were male soccer players. The rehabilitation protocols were similar for both groups except the 8-month group delayed jogging and isokinetic strengthening for an additional 4 weeks beyond the 4- to 5-month time point when the 6-month group initiated these activities. Both groups delayed full weight bearing until 3 months postoperatively. Outcome was assessed by Lysholm, instrumented laxity, isokinetic strength, 1-leg hop, figure 8 running, and return to sports.

The 6-month group performed better at 8 months for running and strength testing. No differences existed between the 2 groups at 12 months. Two patients in the 8-month group did not return to sports due to early arthrosis. Based on this study, no significant conclusions can be made regarding the difference in 6-month versus 8-month rehabilitation.

Beynnon et al,[2] in a 2005 study, performed a prospective, randomized, double-blind comparison of ACL rehabilitation programs administered for 2 different time intervals. A power analysis was performed to determine the number of patients required to detect a 2.5-mm difference in knee laxity between treatments. Twenty-five patients were randomized to an identical ACL rehabilitation program, with the only difference being the time frame during which it was administered. One group (accelerated) performed the protocol for 19 weeks, and the second group (nonaccelerated) performed the same protocol over 32 weeks. Exclusion criteria included meniscal repair, grade 4 chondral lesions, and significant concomitant ligamentous injuries. Randomization was performed by a random number generation program. Three patients were lost to follow-up, leaving 10 in the accelerated group and 12 in the nonaccelerated group.

Compliance with the program differed between the 2 groups. Although compliance was equal at 16 weeks in both groups, by the completion of the program, compliance differed. In the accelerated group, 68% were compliant to the end of the 19-week program, whereas only 40% of the nonaccelerated group was compliant through the end of the 32-week program.

Results were assessed using KT-1000 testing, Knee Injury and Osteoarthritis Outcome Score and International Knee Documentation Committee outcome measures, Tegner activity level, 1-leg hop, and the biochemical markers of articular cartilage metabolism in synovial fluid. Follow-up was performed through 24 months. There was no statistically significant difference between the 2 groups in any parameter measured at any time point. The authors concluded compliance with any ACL rehabilitation program is difficult past 12 weeks, but that in this study, accelerated rehabilitation for 19 weeks did not result in deleterious effects compared with a 32-week program.

MISCELLANEOUS

Ten randomized controlled trials have addressed more discrete issues in single studies regarding ACL reconstruction rehabilitation. Draper,[8] in a 1990 study, evaluated the effect of EMG biofeedback on recovery of the quadriceps muscle following ACL reconstruction. Twenty-two patients were randomly assigned either to routine protocol or routine protocol plus biofeedback performed during straight-leg raises and quadriceps sets for the first 12 weeks of rehabilitation. The randomization method was not reviewed. Results were assessed using isometric strength of 12 weeks and the time to full knee extension. A significant treatment effect was noted in the biofeedback group for quadriceps isometric strength return ($P < .01$). The time to obtain full extension was 63 days in the biofeedback group versus 78 days in the routine group; this difference was significant ($P = .033$).

One study was performed by Tovin et al[31] in 1994 to evaluate the effects of performing rehabilitation exercises in water compared with traditional land training. Twenty patients were randomized following bone-patellar tendon-bone autograft ACL reconstruction using a block, coin toss, alternating randomization technique. The land group performed traditional rehabilitation exercises with a closed chain emphasis for the first 8 weeks. The water group performed a similar exercise program in the pool with water resistance and some modification of the rehabilitation program for weeks 2 through 8.

Thigh girth, knee effusion, and knee passive range of motion were evaluated at 2-week intervals during the 8 weeks. Isokinetic and isometric peak torque, instrumented knee laxity, and Lysholm scores were obtained at 8 weeks. Knee laxity was equivalent in both groups. Range of motion was equivalent in both groups. Isokinetic peak flexion torque was increased in the land group (P = .01). The water group demonstrated less knee effusion at 8 weeks. Lysholm score was greater in the water group than in the land group at 8 weeks (92.2 versus 82.4, respectively; P = .03).

Blanpied et al,[3] in a 2000 study, assessed the effectiveness of adding a slide board home exercise program 2 times per week to a standard physical therapy regimen. Fourteen patients were randomly assigned to 2 groups 8 weeks following ACL reconstruction using a bone-patellar tendon-bone autograft. The intervention group used a lateral slide board 3 times per week in addition to a standard physical therapy regimen during weeks 8 through 14. The intervention group gradually increased their time on the slide board to three 12-minute sessions with a 3-minute rest between sets during week 6. The control group continued with standard physical therapy. Randomization, blinding, and the use of independent observers were not discussed.

Parameters assessed included isometric peak extension and flexion torque, maximum lateral step height, and lateral step up repetitions to fatigue. The authors did not normalize their data to the opposite extremity. Thus, their analysis and conclusions may be flawed. The slide group demonstrated increased peak extension torque from pretest values. Peak flexion differences were not significant. Lateral step height increased significantly from pretest to posttest in the slide group. Both groups demonstrated significant improvement from pretest to posttest on lateral step up repetitions to fatigue. The authors concluded the lateral slide board exercises improved knee extension strength.

Cupal and Brewer,[5] in a 2001 study, examined the effects of relaxation and guided imagery on the strength, reinjury anxiety, and pain following ACL reconstruction. Thirty patients were randomly assigned to 3 groups: treatment, placebo, and control. Randomization was performed by random block assignment procedures to ensure equal group sizes. The treatment group received 10 individual sessions of relaxation and guided imagery in addition to normal physical therapy during the first 6 months of rehabilitation. Treatment sessions were scripted and audiotaped, and were identical for all participants. Participants were asked to listen to the audiotapes at least once daily. The placebo group received attention, encouragement, and support in addition to their normal physical therapy. Each placebo participant was asked to devote 10 to 15 minutes per day visualizing a peaceful scene. The control group underwent a normal physical therapy course.

Results were evaluated using isokinetic knee strength testing, a 0 to 10 reinjury anxiety score, and pain score at 24 weeks. The treatment group demonstrated a significant increase in isokinetic strength at 24 weeks ($P < .05$). Reinjury anxiety and pain decreased more significantly in the treatment group ($P < .05$). Compliance with daily audiotape listening averaged 4.4 times per week. The authors concluded a relaxation-based and imagery-based psychological intervention program may facilitate recovery from ACL reconstruction.

Meyers et al,[16] in a 2002 study, compared stair climber versus cycle ergometry in ACL reconstruction rehabilitation. At the 4-week postoperative point, 46 patients were randomized to 3 sessions a week using a stair climber or cycle equalized for workload. Randomization was not discussed.

Parameters assessed included isokinetic strength testing at 4 and 12 weeks, leg girth, KT-1000 testing, and subjective evaluation. The only outcome for which a difference was noted was increased gastrocnemius circumference in the stair stepper group. The authors concluded a stair climber is a viable and safe alternative to cycle use for postoperative ACL reconstruction rehabilitation.

Liu-Ambrose et al,[15] in a 2003 study, evaluated proprioceptive or strength training 6 months after ACL reconstruction. Ten patients were randomly allocated to strength training by a method of increased loading versus a proprioceptive training program that was progressed by decreasing the support base, decreasing surface stability, increasing repetition number, removing visual feedback, and increasing the complexity and speed of the training. Both programs lasted 12 weeks with sessions held 3 times per week. Patients were randomized if they were >6 months (range, 6-27 months; 9 of 10 patients ranged from 6-10 months) following semitendinosus hamstring autograft reconstruction. The strength group consisted of 3 men and 2 women. The proprioception group consisted of 1 man and 4 women. On average, the strength group was 12.2 months postoperatively, compared with 6.7 months for the proprioception group. Randomization, blinding, and independent assessment were not addressed in the article. Compliance was assessed by use of a training log.

Outcome measures were Lysholm and Tegner scores, average isokinetic torque, functional hop tests, and hamstring peak torque time. Patients were assessed 6 and 12 weeks after beginning the training programs. Lysholm and Tegner scores increased significantly in both groups, but there was no difference between the 2 groups. The proprioception group demonstrated a greater change in isokinetic torque compared with the strength group after 12 weeks of training (hamstring, $P = .04$; quadriceps $P = .005$). Both groups showed statistically significant increases in their functional hop tests, but there was no difference in the increase between groups. Peak torque time decreased in the proprioception group at 6 weeks and then returned to baseline at 12 weeks. In the strength training group, peak torque time actually increased at 6 weeks and then returned to baseline at 12 weeks. The authors hypothesize this may be caused by the strength training program, which emphasized slow muscle training versus the peak torque time, which emphasized fast recruitment testing.

Prior to the study, the authors performed a power analysis to detect a 10% to 12% difference in peak torque time. Their study did not detect a difference this large and thus may have been underpowered. The authors concluded proprioceptive training and strength training both were beneficial for improving functional ability and subjective scores. The limitations of the study included selection bias by choosing groups dissimilar regarding gender and time from surgery.

Ohta et al,[20] in a 2003 study, evaluated low-load resistance muscle training with moderate restriction of blood flow following ACL reconstruction using a quintupled semitendinosus autograft. Forty-four patients were randomized to 2 groups using odd or even identification numbers. Starting at week 2, the restricted blood flow group placed a tourniquet on the proximal thigh of the operated side and inflated it to 180 mm Hg while performing their rehabilitation exercises. The tourniquet was inflated for a maximum of 15 minutes, followed by a 15- to 20-minute rest period and then resumption of exercises with the tourniquet. An exercise log was kept to determine exercise achievements. Two patients from the tourniquet group dropped out because of discomfort.

Results were measured using isokinetic testing, cross-sectional thigh area, and muscle fiber diameter by biopsy preoperatively and at 16 weeks postoperatively. Isokinetic preoperative ratios of injured strength to healthy strength were equal. Postoperatively at 16 weeks, in the restricted blood flow group, the extensor muscle strength was stronger for all measurements ($P \leqslant .004$). Flexor muscle strength measurements also were significantly improved in the restricted blood flow group ($P \leqslant .05$ or better). Cross-sectional area by MRI was increased in the extensor muscles in the restricted blood flow group ($P = .04$). No significant difference was noted in the cross-sectional area of the knee flexor group. No significant difference was noted in muscle fiber biopsies.

Decker et al,[6] in a 2004 study, evaluated gait retraining following patellar tendon ACL reconstruction. Sixteen patients were randomly assigned 2 groups. Randomization, blinding, and use of independent observers were not addressed. Both groups performed identical rehabilitation protocols until the 6-week mark. At that point, group 1 began a walking program with the aid of the metronome set at a stride frequency calculated by a modified force driven harmonic oscillator. The second group began a walking program at a preferred stride frequency without the use of a metronome. Both groups were asked to walk 3 times per week for 20 to 30 minutes, and both groups kept an exercise log. Compliance with the program was similar in both groups.

Results were assessed by gait analysis at 6 and 12 weeks postoperatively. At 6 weeks, both groups noted decreased stride frequency and velocity. At 12 weeks, the metronome group had an improved midstance knee range of motion and improved extension at ground contact ($P < .05$). The authors believe gait changes may contribute to prolonged quadriceps weakness.

Tyler et al,[32] in a 2004 study, evaluated the effect of creatine supplementation on strength recovery following ACL reconstruction. The study was a randomized, placebo-controlled, double-blind trial involving 60 patients following endoscopic bone-patellar tendon-bone autograft ACL reconstruction. The method of randomization was not reviewed in the article. Patients were given 20 g/day for 7 days beginning the first postoperative day, followed by 5 g/day for 11 weeks.

Results were assessed using isokinetic testing at 6, 12, and 24 weeks postoperatively, knee outcome score, and a 1-leg hop test preoperatively and at 6 months postoperatively. No significant differences were noted in either group with any of the parameters tested at any time point. Attrition bias may have affected the study. Thirty-eight patients (17 creatine and 21 placebo) were available at 6-month follow-up. Patients were lost to follow-up for a variety of reasons, including noncompliance, surgical complications, and gastrointestinal distress. The authors concluded creatine supplementation did not demonstrate a beneficial effect during the first 12 weeks following ACL reconstruction.

Shaw et al,[25] in a 2005 study, evaluated the effect of early quadriceps exercises following ACL reconstruction. One hundred three patients were randomized using concealed allocation methods to 2 groups. Both groups performed range of motion; active knee flexion; passive knee extension; gait education; and foot, ankle, and calf exercises. The quadriceps exercise group added quadriceps sets and straight-leg raises with 10 repetitions 3 times per day.

Results were assessed using KT-1000 testing at 3 and 6 months, isokinetic testing, and hop test at 6 months, range of motion, quadriceps lag, limb circumference, pain, and satisfaction at 1 day, 2 weeks, and 1, 3, and 6 months. The Cincinnati knee rating scale was used at 1, 3, and 6 months. Significant differences were noted in active flexion and extension at 1 month, with the quadriceps exercise group improved ($P = .05$). No differences were noted in quadriceps lag or limb circumference at any time point. No difference in pain was noted except at 1 day when the quadriceps exercise group noted pain while performing the exercises. With the sports subscores of the Cincinnati scale, symptoms and problems were significantly improved in the quadriceps exercise group at 6 months. KT-1000 testing was similar in both groups at all time points. The authors concluded early quadriceps exercises are not deleterious and may improve some facets of ACL rehabilitation.

CONCLUSION

Many issues regarding ACL reconstruction rehabilitation have been evaluated using randomized controlled trials. The methodologic quality of the studies reviewed is mixed. Most of the studies have some form of potential bias. This is especially true of the studies published prior to 2000, when many of the study quality issues were not yet recognized. Despite this, some reasonable conclusions can be made from the studies and used in developing an ACL reconstruction rehabilitation protocol.

Early weight-bearing appears beneficial and may decrease patellofemoral pain. Early motion is safe and may help avoid problems with later arthrofibrosis. Continuous passive motion is not warranted to improve rehabilitation outcome in patients and can avoid the increased costs associated with CPM. Minimally supervised physical therapy in selected motivated patients appears safe without significant risk of complications. Until further studies are performed, protocols should use closed kinetic chain exercises in the first 6 weeks. Postoperative rehabilitative bracing either in extension or with the hinges opened for range of motion does not offer significant advantages over no bracing.

Neuromuscular electrical stimulation, if deemed necessary for patients, should be instituted early in the postoperative period and should be of high intensity to achieve meaningful results. Accelerated rehabilitation appears safe, at least in the 5-month to 6-month time frame as demonstrated by the studies by Beynnon et al[2] and Ekstrand.[10] Further studies are necessary to determine whether shorter time frames are safe.

As seen in the miscellaneous section, water-based therapy, stair climber, and slide board exercise programs appear safe and may add variety if available for patients. Gait, proprioception, and psychological training may be of some benefit. Creatine, at least in the dosage and time frame used by Tyler et al,[32] offered no benefit. Restricting blood flow during rehabilitation sessions requires further studies before it becomes regularly prescribed by most clinicians. Despite more than 50 randomized controlled trials in the field, many questions remain, and further studies are warranted to continue to add evidence to our ACL reconstruction rehabilitation protocols.

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