Neuromuscular Training Versus Strength Training During First 6 Months After Anterior Cruciate Ligament Reconstruction: A Randomized Clinical Trial

May Arna Risberg, Inger Holm, Grethe Myklebust, Lars Engebretsen

Background and Purpose

The purpose of this study was to determine the effect of a 6-month neuromuscular training (NT) program versus a traditional strength training (ST) program following anterior cruciate ligament (ACL) reconstruction.

Subjects

Seventy-four subjects with ACL reconstruction participated in the study.

Methods

The study was a randomized, single-blinded, controlled trial. The NT and ST groups were tested preoperatively and at 3 and 6 months. The main outcome measure was the Cincinnati Knee Score. Secondary outcome measures were visual analog scales (VASs) for pain and function, the 36-Item Short-Form Health Survey (SF-36), hop tests, isokinetic muscle strength, proprioception, and static and dynamic balance tests.

Results

The NT group demonstrated significantly improved Cincinnati Knee Scores and VAS scores for global knee function compared with the ST group at the 6-month follow-up. There were no significant differences between the groups for the other outcome measures (ie, hop, balance, proprioception, and muscle strength tests).

Discussion and Conclusion

The results of this study suggest that exercises included in the NT program should be part of the rehabilitation program following ACL reconstruction.

MA Risberg, PT, PhD, is Associate Professor and Chairman, Norwegian Research Center for Active Rehabilitation (NAR), Orthopedic Center, Ullevaal University Hospital; Norwegian Sport Medicine Clinic (NIMI); and Norwegian School of Sport Sciences, Oslo, Norway. Address all correspondence to Dr Risberg at: mayarnarisberg@hotmail.com.

I Holm, PT, PhD, is Professor, Rikshospitalet Medical Center, University of Oslo, Oslo, Norway.

G Myklebust, PT, PhD, is Associate Professor, Norwegian Sport Medicine Clinic (NIMI) and Norwegian School of Sport Sciences, Oslo, Norway.

L Engebretsen, MD, PhD, is Professor and Chairman, Division of Neuroscience and Musculoskeletal Medicine, Ullevaal University Hospital, and Faculty of Medicine, University of Oslo.

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Anterior cruciate ligament (ACL) rupture is a serious knee ligament injury, causing severe functional problems that seem to be unrelated to the degree of knee joint laxity.[1] The re-establishment of neuromuscular control of the lower extremity has recently been recognized as one of the keys to restoring dynamic joint stability and functional movement patterns.[2,3] Neuromuscular control results in avoidance of subluxations,[4] with the subsequent reduced risk of further injuries. Lack of neuromuscular control of the lower extremity and muscle strength (force-generating capacity) are 2 of the main impairments following ACL injury and, therefore, are often a component of rehabilitation after the injury.[2,5,6] Activities of daily living and sport activities require coordinated neuromuscular control and muscle strength sufficient to perform the required movements and activities. Therefore, the aim of rehabilitation programs for people with ACL injury is to normalize dynamic knee joint stability and muscle strength of the lower extremity.

Some authors[7,8] have reported differences in neuromuscular performance in ACL-deficient and reconstructed knees. Other authors[9] have highlighted the importance of regaining quadriceps femoris muscle strength following ACL reconstruction. Therefore, both muscle strength training (ST) programs and neuromuscular training (NT) programs have been implemented to restore knee function after ACL injury and reconstruction. Several NT programs have been evaluated for injury prevention[10,11] and for patients with ACL deficiency,[12,13] but these programs have not been studied thoroughly in subjects with ACL reconstruction.[14] To our knowledge, only 2 randomized controlled trials[14,15] have been conducted on NT versus traditional ST programs. Therefore, more evidence for differences among the exercises used in clinical practice today for rehabilitation after ACL reconstruction was needed.

We hypothesized that NT programs would be superior to traditional ST programs for restoring knee function. The primary objective of this study was to determine the effect of an NT program versus a traditional ST program on knee function (Cincinnati Knee Score)[16] following ACL reconstruction. A secondary aim was to evaluate the effect on muscle strength, other patient-related outcome measures (visual analog scale [VAS] and 36-Item Short-Form Health Survey [SF-36]),[17] pain, functional performance (hop tests), proprioception, and balance.

Material and Methods

Subjects

Seventy-four subjects (27 female and 47 male) with a mean age of 28.4 years (range=16.7–40.3) were included in this single-blinded, randomized controlled trial. All subjects were scheduled for ACL surgery at our hospital, were between the ages of 15 and 40.9 years, were candidates for arthroscopic reconstruction of the ACL using an autogenous bone-patellar tendon-bone (B-PT-B) graft, and lived close enough to participate in rehabilitation at the 2 outpatient clinics included in this study. The B-PT-B graft was the reconstruction method of first choice at our hospital. Subjects were excluded if the ACL tear had occurred more than 3 years prior to surgery, they had tears of the menisci that required repair, they had previous injury or surgery to either knee, there was evidence of degenerative arthritis on radiographs or articular cartilage fissures extending to subchondral bone, or exposed bone was seen on arthroscopy (grade IV).

Procedure

Before discharge from the hospital, the subjects were randomly assigned to participate in 1 of the 2 rehabilitation programs. The participants of the NT program were 13 female subjects with a mean age of 27.2 years (range=20.6–37.9) and 26 male subjects with a mean age of 27.7 years (range=16.7–39.6). The participants of the ST group were 14 female subjects with a mean age of 26.5 years (range=19.8–38.0) and 21 male subjects with a mean age of 31.2 years (range=19.4–40.3). Both groups were given specific instructions by the research assistant for the completion of the exercise routines. Simple randomization was used by our statistician using a computer-generated table of random numbers. One investigator kept the assignment scheme and provided the assignment to the treating physical therapists in a series of consecutively numbered opaque envelopes. Allocation was concealed from the outcome assessor and participants at all times and from the physical therapist until the point of treatment.

Sample size was calculated based on the Cincinnati Knee Score as the main outcome measure and on a predetermined difference between treatment groups of 10 points change on the Cincinnati Knee Score. This figure was based on the results of a previous study by our group[18] and a comparative study[19] and was considered to be clinically relevant. A standard deviation of 13 points for the Cincinnati Knee Score was used in our power calculations based on previous studies.[9,20] To detect a difference of this magnitude with a power of 90% at the $P<.05$ significance level, 36 subjects were needed in each group, requiring a minimum of 72 subjects. We initially aimed for 100 subjects to allow for dropouts.

Both rehabilitation programs lasted for 6 months, which is the customary length of time for rehabilitation programs after ACL surgery in Norway. No knee braces were used following the knee surgery or during the rehabilitation program.

Two sets of 2 senior expert physical therapists completed preoperative and follow-up test examinations, all masked to the randomization procedure and group allocation. Each subject was tested preoperatively for baseline measurements and returned for follow-up evaluations at 3 and 6 months. The rehabilitation programs were administered at 2 outpatient rehabilitation centers (the ST program at the Norwegian Sport Medicine Clinic and the NT program at the Department of Physical Medicine and Rehabilitation, Ullevaal University Hospital). At each center, 2 physical therapists were responsible for the rehabilitation program. All subjects signed an informed consent form prior to participation.

Knee Function—Outcome Measurements

The Cincinnati Knee Score was the primary outcome measurement. This instrument has been well-validated as an outcome measure.[9,16,18] The questionnaire consists of the following variables: pain, swelling, giving way, general activity level, walking, stair climbing, running, jumping, and twisting activities. The maximum score is 100 points, indicating a normal knee. The Cincinnati Knee Score has shown good reliability, with an intraclass correlation coefficient (ICC) of .88 for test-retest reliability.[21]

Two VASs were included: one for pain intensity and one for global knee function. For both scales, the subjects made a mark on a 100-mm line between 2 extremes. For pain intensity, the subjects were asked to rate their pain intensity during activities or immediately after activities on the VAS, with 0 representing no pain and 100 representing worst pain ("as much pain as one can possibly imagine").[22,23] For the VAS for global knee function, 0 represented the worst possible knee function and 100 represented the same knee function as prior to the knee injury.[18,24] To our knowledge, the reliability of data for the VAS for global knee function, where the subjects themselves marked a line on a 100-mm line, have not been examined, but some authors[25] have reported reliability data for a numeric VAS, and other authors[26] have reported reliability data for a knee questionnaire using VAS responses for the items.

Muscle strength measurements of the quadriceps femoris and hamstring muscles were obtained using the Cybex 6000* isokinetic dynamometer[27,28] preoperatively and at the 6-month follow-up. The test protocol consisted of 5 repetitions at an angular velocity of 60°/s (strength) followed by a 1-minute rest period and 30 repetitions at 240°/s (endurance). The parameter used for analysis was total work.[27] Side-to-side differences in strength between injured and noninjured legs were calculated using the strength index: (injured leg/noninjured leg) × 100. Previous work has shown good to high reliability for isokinetic muscle strength tests, with ICCs ranging from .81 to .97.[29]

Balance was recorded using static and dynamic balance tests on an instrumented unstable platform (KAT2000†), which has been evaluated in previous studies.[30,31] The KAT2000 is a circular platform on a base of a pneumatic bladder, inflated with air to adjust for test difficulty and to allow for normalization to the subject's body weight. A tilt sensor on the platform was connected to a computer, which registered the deviation of the platform from a reference position 18.2 times each second. The distance from the central point to the reference position was measured at every registration. From the summation of these distances, a score—the balance index—was calculated. A low balance index indicates good ability to perform the balance task.

Each subject completed a 1-leg static balance test on each leg (3 trials on each leg) and a 2-leg dynamic test (3 trials). The average of the 3 trials was used as the balance index. The position of the feet was recorded, and the same position was identified at the follow-up tests. The subjects were not given any practice trials prior to the testing, but they received thorough information on what to do during the test. Hansen et al[30] reported that, for a group of 25 subjects tested on the KAT2000, a diminution of 12% from test to retest was needed for the dynamic balance test and a diminution of 15% from test to retest was needed for the static balance test to detect changes in balance due to interventions; otherwise, the changes probably would be due only to test or subject variations. However, no other reliability data for the KAT2000 have been reported.

Proprioception was evaluated using a joint kinesthesia measure called the "threshold to detection of passive motion" (TTDPM) device.[32,33] The device moves the knee joint into flexion or extension with a constant angular velocity of 0.5°/s. All testing was performed at a starting position of 15 degrees of knee flexion. Subjects were told that either leg could move into flexion or extension beginning at a random time interval between 0 and 45 seconds after the examiner started the test. Once the subject detected motion of the leg, a button was pressed and the subject stated which leg was moved and in which direction (flexion or exten-

* Cybex International Inc, 10 Trotter Dr, Medway, MA 02053.

† Breg Inc, 2611 Commerce Way, Vista, CA 92081.

sion). Each trial consisted of 3 repetitions for each of the 4 motions (flexion and extension of both legs), resulting in a total of 12 repetitions. In the case of incorrect identification of the motion, the repetition was returned to the randomization list so that 3 correct repetitions of each motion were completed. The number of incorrect responses was recorded. A reliability coefficient (ICC) of .83 has been reported for the TTDPM.[33]

Knee performance was tested with 3 functional knee tests (one-leg hop test, triple-jump test, and stair hop test) that were used in previous ACL studies.[34,35] The one-leg hop and triple-jump tests were performed 2 times on each leg, and the best value (distances measured in centimeters) was recorded. For the stair hop test, the subjects were asked to hop up and down 22 steps (step height=17.5 cm) on one leg and to repeat the activity on the other leg (time measured in seconds). For all 3 functional tests, the procedure was first performed on the noninjured leg followed by the injured leg. Side-to-side differences in performance between noninjured and injured legs were calculated using the index: (injured leg/noninjured leg) × 100. The one-leg hop test has shown good reliability, with ICCs ranging from .97 to .99.[36] Reliability coefficients (Pearson *r*) ranging from .81 to .97 have been reported for the triple-jump test and the stair hop test, with coefficients of variation ranging from 2.1% to 3.8%.[37]

Health-related quality of life was assessed using the SF-36.[17,38] The instrument is divided into 8 subscales (physical function, role limitations–physical, role limitations–emotional, bodily pain, general health, vitality, social function, and mental health). Each subscale of the SF-36 is scored on a scale of 0 to 100, with the higher the score, the better the person's health status. Reliability for the Norwegian version of the SF-36 has been documented using the Cronbach alpha.[39] All 8 subscales have been reported to exceed the .70 standard for group comparison, and the Cronbach alpha exceeded the .90 standard for individual comparisons on the physical functioning subscale.[39] Finally, knee joint laxity was recorded using the maximum manual KT-1000[‡] knee arthrometer test.[40] The KT-1000 arthrometer has shown to be a reliable instrument, with reported ICCs between .91 and .97[29] for the involved knee, and with better interrater reliability for expert raters compared with novice raters.[41]

Rehabilitation Programs

Current research on the effects of NT and ST; knowledge about graft healing; research on proprioception, neuromuscular control, and quadriceps femoris muscle strength deficits after ACL reconstruction; and our clinical experience were considered during the design of our rehabilitation programs. The traditional ST program was widely used when we started the study, whereas the neuromuscular exercises had started to be used in physical therapist practices. We included a 6-month rehabilitation program in this study because of the current practice in Norway in which all individuals undergo a 6-month supervised rehabilitation program after ACL reconstruction, which is covered by the social security system.

The subjects were hospitalized for 1 to 3 days following ACL reconstruction. After being discharged from the hospital and until the rehabilitation program started at the outpatient clinic, the subjects carried out a home program with the main focus on restoring full range of motion (ROM) and swelling reduction. Both rehabilitation programs started the second week after surgery at the outpatient clinics, with treatment sessions 2 to 3 times a week, and continued for 6 months. To reduce swelling, we recommended that the subjects keep the injured leg elevated and perform ankle plantarflexion and dorsiflexion ROM exercises and isometric quadreiceps femoris and hamstring muscle exercises. Crutches also were used to reduce swelling and to improve gait. Full knee extension is the most important goal the first week of rehabilitation. Gravity is used to restore full knee extension by the use of 2 chairs, with the leg elevated on a hard pillow under the heel when sitting or with the leg elevated on the edge of the bed in a supine position.

NT program. The NT program was divided into 6 phases of 3 to 5 weeks each and consisted of balance exercises, dynamic joint stability exercises, plyometric exercises, agility drills, and sport-specific exercises (Appendix 1).[42] Subjects who developed pain, swelling, or ROM deficits underwent interventions (cryotherapy, patellofemoral taping, and ROM exercises) until these impairments were resolved. In addition to amount of pain and swelling, criteria used to determine readiness for progression were the ability to maintain balance of the position (static balance) before movements were superimposed on the position (dynamic balance) and awareness of the position of the body in space before tolerating movements or perturbations.

Balance exercises included single- and double-leg stance on even, flat surfaces, with progression to balance on a mat, a wobble board, and a trampoline. Some of the dynamic joint stability exercises were performed using vectors on the floor to reference the start and the direction of the exercises described by Gray.[43] Plyometric exercises (jump training

‡ MEDmetric Corp, Street 7542 Trade St, San Diego, CA 92191.

exercises) were used to improve or change technical performance and to improve shock absorption during landing. Furthermore, agility training exercises were included to allow the subjects to adapt to quick changes in direction and to acceleration and deceleration during cutting activities. Further details of the rehabilitation program and the specific exercises are available elsewhere.[12]

ST program. The ST program consisted mainly of ST exercises of the lower-extremity muscles, with emphasis on the quadriceps femoris, hamstring, gluteus medius, and gastrocnemius muscles. All exercises in the ST program were based on American College of Sports Medicine (ACSM) recomendations[13] and current practice in our clinic for people with ACL reconstruction. Subjects who developed pain, swelling, or ROM deficits underwent treatments until these impairments were resolved. This program has not been described or published previously, and the exercises are described in Appendix 2.

The ST program was divided into 4 phases. The goal of phase 1 was to reduce swelling and increase ROM, especially knee extension ROM. Exercises in phase 1 were ROM exercises in prone and supine positions, in addition to the use of a stationary bicycle. Initially, subjects used the stationary bicycle with a pendulum movement. After the training sessions, cold therapy was applied for approximately 20 minutes.

Phase 2 started when pain and swelling were reduced. Weight bearing during the exercises was emphasized to normalize gait and to control knee movements. The "knee over toe" position, core stability with pelvic and hip control, subjects' awareness of position of lower-extremity joints, and changes in weight bearing during the exercises were emphasized during the training sessions. A mirror was used to provide feedback and to ensure correct movements. If the subjects did not perform the exercises as intended, they returned to those exercises that they were able to perform in a controlled manner. Instructions such as "knee over toe" and "hips in plane" were commonly used during the exercises.

In phase 3, a full ST program was introduced in addition to one balance exercise (single-leg stance balance exercise in a pulley apparatus). Moderate- to high-intensity ST was included based on each subject's abilities to tolerate increased loading (weights). Recommended frequency and dose of exercises (3 sets, 2–3 days a week, of 50%–80% of their 1-repetition maximum)[14] were used, starting out with 12 to 15 repetitions and progressing to fewer (8–12) repetitions. When the subjects performed the exercises in a controlled manner, weights and resistance were increased. After 13 to 16 weeks, depending on their knee function and lower-extremity performance, the subjects started running on a treadmill with a few degrees of inclination to reduce the stress on the ligamentum patellae. Increased running distance, speed, and inclination were used, depending on their knee function and their preinjury activity level.

In phase 4, the ST exercises involved decreased repetitions and increased weights (3 sets of 6–8 repetitions), which were individually adjusted. For subjects who wanted to return to sports, sport-specific exercises based on their previous sport activities were introduced.

Adherence to the Rehabilitation Programs

Each subject was required to fill out daily log sheets at the outpatient clinics to document their adherence to the rehabilitation program in addition to other exercises or training that they did elsewhere. This information was reviewed by the physical therapist initially and by the research assistant on a weekly basis. The training diary included both number of visits for physical therapy intervention and hours spent exercising during the rehabilitation program, in addition to number of other exercise sessions and hours spent doing other exercise activities. Eighty percent adherence, meaning 80% of the recommended physical therapy visits (2 times a week for 6 months), was set as the definition for being adherent to the rehabilitation program.

Data Analysis

Data were analyzed using a repeated-measures analysis of variance (ANOVA) with time as the repeated-measures factor for the outcome measures at the 3- and 6-month follow-ups and as the between-groups factor for rehabilitation programs (NT and ST). In addition, Student t tests were used to determine group differences (NT and ST) at the 6-month follow-up as well as for time of test differences. Mann-Whitney U tests were used when parametric assumptions were not fulfilled. Effect size was calculated using change in scores divided by standard deviation at baseline.[15] An effect size above 0.8 refers to a large change, and an effect size above 0.6 refers to a moderate change.[15] A probability level of $P<.05$ was used to show statistical significance.

Results

Eighty-one subjects were eligible for the study based on the inclusion criteria and preoperative evaluation. After application of intraoperative exclusion criteria, 74 subjects were ultimately included in the study and randomly assigned to the ST group (n=35) or the NT group (n=39). The 7 subjects who were tested preoperatively but not included in the

Table.
Mean (SD) Outcome Measurements for the Strength Training (ST) Group and the Neuromuscular Training (NT) Group Preoperatively and 3 and 6 Months Postoperatively[a]

	Preoperative (n=74)		3 mo (n=67)		6 mo (n=65)	
	ST Group (n=35)	NT Group (n=39)	ST Group (n=31)	NT Group (n=36)	ST Group (n=31)	NT Group (n=34)
KT-1000 (mm difference)	7.9 (3.6)	7.2 (4.3)	2.6 (2.9)	2.9 (2.8)	3.0 (2.9)	3.4 (2.6)
Cincinnati Knee Score	65.3 (13.0)	65.2 (17.0)	61.4 (11.7)	64.3 (11.5)	73.4 (9.6)	80.5 (12.3)[b]
VAS for pain during activity (mm)	35.4 (23.3)	35.2 (26.5)	25.9 (18.6)	31.8 (22.6)	24.6 (20.3)	20.7 (21.0)
VAS for knee function (mm)	33.9 (25.3)	39.1 (25.5)	51.7 (26.0)	50.1 (23.8)	59.3 (23.1)	72.4 (22.1)[c]
Triple jump test (%)	94.6 (10.2)	91.8 (12.3)			83.1 (15.4)	88.5 (10.4)
One-leg hop test (%)	93.7 (11.3)	90.1 (15.5)			81.0 (18.2)	84.9 (10.9)
Stairs hop test (%)	84.8 (18.1)	78.4 (21.0)			79.8 (16.4)	79.8 (25.7)
Balance index, static, uninvolved leg[d]	566 (266)	557 (246)	509 (170)	457 (218)	443 (156)	433 (168)
Balance index, static, involved leg[d]	602 (258)	592 (311)	532 (211)	455 (170)	460 (159)	445 (191)
Balance index, dynamic[d]	1,100 (451)	947 (266)	911 (335)	850 (311)	917 (394)	769 (235)
Proprioception[e] (TTDPM), uninvolved leg (°)	1.22 (0.67)	1.19 (0.66)	1.13 (0.45)	1.04 (0.52)	1.21 (0.52)	1.22 (0.86)
Proprioception[e] (TTDPM), involved leg (°)	1.14 (0.74)	1.02 (0.52)	1.39 (0.90)	1.13 (0.45)	1.22 (0.52)	1.20 (0.76)
Flexion total work 60°/s (%)	80.6 (19.5)	82.9 (20.4)			88.3 (14.4)	86.3 (14.3)
Flexion total work 240°/s (%)	87.6 (18.4)	86.8 (24.2)			94.7 (16.1)	90.8 (21.1)
Extension total work 60°/s (%)	79.0 (18.0)	79.4 (20.6)			67.3 (16.1)	79.1 (17.1)
Extension total work 240°/s (%)	84.7 (12.8)	83.7 (17.9)			78.0 (16.0)	79.0 (16.8)

[a] There were significantly improved Cincinnati Knee Scores and visual analog scale (VAS) scores for knee function at 6 months in the NT group compared with the ST group. TTDPM=threshold to detection of passive motion.
[b] $P=.05$.
[c] $P=.02$.
[d] Total number of subjects=51.
[e] Total number of subjects=47.

study had a hamstring muscle graft (surgeon was not aware of the fact that the subjects were eligible for the study), had a cartilage injury down to subchondral bone, did not have a complete ACL injury, did not show up at the time of surgery, or had a meniscus repair. Mean time from injury to surgery was 46.4 weeks (range=7.4–152.9), and there were no significant differences between groups. Thirty-four subjects (46%) had meniscus injuries, and 29 subjects (45%) had grade I, II, or III cartilage injuries. Nineteen subjects (30%) had both meniscus injuries and cartilage injuries. All of the meniscus injuries were debrided, and no additional treatment was required for those with cartilage injuries.

One subject who was included in the study moved out of the city soon after surgery. She could not attend the rehabilitation program and did not return for follow-up examination. Sixty-seven subjects (92%) returned for follow-up examination at 3 months, and 65 subjects (89%) returned for follow-up examination at 6 months. Of the 7 subjects who did not return for the 3-month follow-up examination and the 9 subjects who did not return for the 6-month follow-up examination, only 4 subjects (5%) did not return for reexamination after surgery (either 3- or 6-month follow-up).

After subject number 47 had been included, the proprioception device failed and was unable to be repaired within the time frame of the study. As a result, proprioception data were available only for the first 47 subjects. Similarly, the KAT2000 failed after subject 51 was included, and data were available only for the first 51 subjects.

Preoperatively, there were no significant differences between the 2 groups with respect to sex, age, time from injury to operation, knee joint

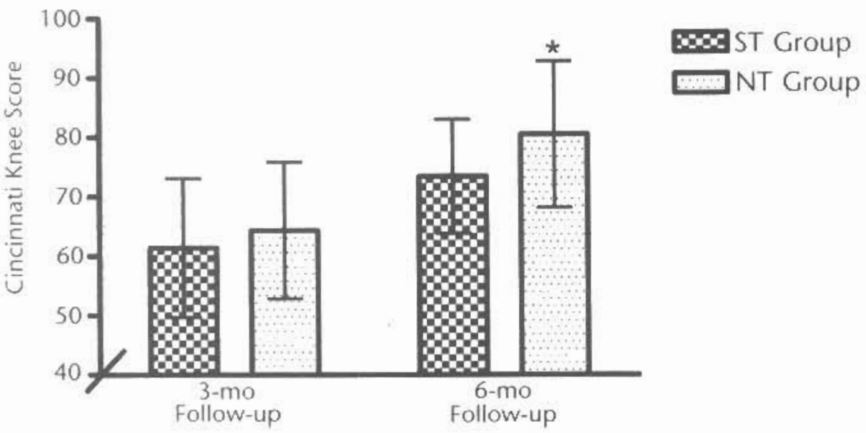

Figure.
Cincinnati Knee Score at 3- and 6-month follow-ups for the strength training (ST) group and the neuromuscular training (NT) group. Asterisk indicates significant differences between groups at 6 months (P=.01).

laxity, activity level, or any of the other variables that were measured (Table). At 3 months, there were no significant differences between the NT group and the ST group for any of the outcome measurements (Table).

At the 6-month follow-up, after the intervention was terminated, there were significantly improved Cincinnati Knee Scores for the NT group compared with the ST group (P=.01) (Figure). The effect sizes for the Cincinnati Knee Scores were 0.89 for the NT group and 0.65 for the ST group. The NT group also had significantly improved VAS scores for global knee function compared with the ST group (P=.02). The effect sizes were 1.3 and 1.0 for the NT group and the ST group, respectively. There were no significant differences between the 2 groups for pain at rest or pain during activity. The effect sizes for pain during activity were 0.55 for the NT group and 0.46 for the ST group. Furthermore, there were no significant differences between the 2 groups for any of the muscle strength variables or any of the other secondary outcome measures. Both the functional knee tests and the quadriceps femoris muscle strength data showed that there was significant decline in knee function from the preoperative period to the 6-month postoperative period in both groups. These data are in accordance with the findings of our previous study[9] showing that patients are not back to normal strength or knee function 6 months after surgery.

The effect sizes for the dynamic balance tests showed a small change for the ST group from baseline to 6 months (effect size=0.46) and a moderate change for the NT group from baseline to 6 months (effect size=0.60). The effect sizes for the involved leg and the uninvolved leg for the static balance test showed a similar change for both legs from baseline to 6 months (effect sizes of 0.52 and 0.48 for the involved leg and uninvolved legs, respectively, in the ST group and effect sizes of 0.49 and 0.50 for the involved and uninvolved legs, respectively, in the NT group).

Twenty-four subjects in the ST group (77%) and 34 subjects in the NT group (100%) turned in the daily log sheets for program adherence data. There were no significant differences in the number of weeks that the subjects participated in the rehabilitation program between the ST group (20.4 weeks) and the NT group (18.8 weeks) (P=.30). However, the number of physical therapy visits was significantly higher for the ST group (57.6 visits) than for the NT group (42.2 visits) (P=.001), and the mean number of hours spent at the physical therapy outpatient clinic was 62.9 hours for the ST group and 43.8 hours for the NT group (P=.002). There were no significant differences between the 2 groups regarding number of other exercise sessions or hours spent doing other exercises (P=.09 for the ST group and P=.38 for the NT group). The mean number of other exercise sessions and the mean hours spent doing other exercises were 22.0 exercise sessions and 16.2 hours, respectively, for the ST group and 12.9 exercise sessions and 11.0 hours, respectively, for the NT group. In the ST group, 91% of the subjects were categorized as adherent to the rehabilitation program. In the NT group, 71% of the subjects were categorized as adherent to the rehabilitation program.

Discussion and Conclusions

The results of this study indicated that, although there were small differences between the NT program and the ST program, the NT program was superior to the ST program in improving knee function after ACL reconstruction. Our main hypothesis in this study was supported. Subject-reported knee function after ACL reconstruction (as measured with the Cincinnati Knee Score and VASs) was significantly better after 6 months of the NT program compared with 6 months of the ST program. The magnitude of the treatment effect (effect size) for the NT group indicated a large change in subject-reported knee function compared with a moderate treatment effect for the ST group according to the Cohen index.[15] However, there were no differences between the 2 groups for the other secondary outcome measures and no significant differences early (3 months) after surgery. Both training programs provided similar improvements in strength, balance, proprioception, and hop tests.

Previous investigations of the effect of neuromuscular training[13,46,47] have examined subjects with ACL deficiencies. Despite some limitations in these studies, they all demonstrated significantly improved knee function for rehabilitation programs including neuromuscular exercises compared with only strength training exercises for subjects with ACL deficiencies. To our knowledge, only 2 randomized controlled trials[14,15] have been published on the effect of neuromuscular training after ACL reconstruction. Neither of these studies had baseline data (preoperative data), and both studies had major limitations. The study by Liu-Ambrose et al[14] gave limited information on the clinical effect of neuromuscular training, included only 5 subjects in each group, and included the intervention more than 6 months after surgery. They used peak torque time of the hamstring muscles as the main outcome measure, in addition to concentric and eccentric torques of the quadriceps femoris and hamstring muscles, one-legged single-hop test, and Lysholm scale score. The NT group demonstrated a greater percentage of change in isokinetic torques compared with the ST group, but there were no significant differences between the groups for functional ability or subject-reported knee function (Lysholm scale score). The study probably had limited power to detect any differences in Lysholm scale scores or other knee function tests. They concluded that NT alone induced isokinetic strength gains and that restoring and increasing quadriceps femoris muscle strength is essential to maximize functional ability of the reconstructed knee joint.

Cooper et al[15] studied the effect of an NT program versus a traditional ST program during a 6-week intervention (n=15 in each group). The subjects were included 4 to 14 weeks after surgery; the power analysis was based on hop tests, which were included as a outcome measure only at follow-up, and the ST group was significant younger than the NT group. The authors used 2 different graft types (hamstring and patellar tendon), there were more female subjects in the ST group compared with the NT group, and they included only subjects who could walk without crutches, had full ROM, had no quadriceps femoris muscle lag, and had minimal joint effusion. The authors reported no strength measurements, and there were no differences between the 2 groups at follow-up regarding the hop tests. The ST group, however, had less swelling and improved walking and squatting compared with the NT group. Cooper et al concluded that there appeared to be no benefit of performing NT early after ACL reconstruction. Similarly, we found no differences between the 2 rehabilitation groups at 3 months after surgery, but a prolonged rehabilitation program (up to 6 months) seemed to add some benefit for the NT group.

To our knowledge, this is the first randomized controlled trial examining differences between a prolonged rehabilitation program including dynamic knee stabilization exercises, balance exercises, and jump training exercises and a program using primarily ST exercises—2 commonly used exercise programs after ACL reconstruction. The strength of this study, as compared with the 2 previous studies,[14,15] is the length of the rehabilitation program, the number of subjects included in each group based on power analysis, the baseline measurements obtained preoperatively, and the thorough description of both rehabilitation programs. However, there were similarities between the 2 rehabilitation programs that could have had an effect on the lack of differences between the 2 groups. The strength exercises included information to the subjects on controlled knee movements, core stability with pelvic and hip control, and subjects' awareness of position of lower-extremity joints. This information is considered necessary for optimal performance and joint loading during strength exercises. However, this information could be regarded as instructions to improve dynamic stability of the lower extremity during exercises such as squatting and step-up. Additionally, one balance exercise was included in the ST program ("single-leg stance balance exercises," see Appendix 2). Clinical practice today usually includes both strength exercises and neuromuscular exercises,[48] therefore, our aim was to examine potential differences between these 2 common types of exercises included in rehabilitation programs following ACL reconstruction.

Despite some similarities, there were obvious and significant differences between the 2 rehabilitation programs regarding both the type of exercises and the criteria for progression for the ST exercises versus the NT exercises. All the exercises in the NT program were aimed at increasing the individual's ability to dynamically stabilize their knee during activities,[49] activities starting with static balance with progression to dynamic balance (ie, more multifaceted balance exercises and complex jump exercises). Criteria for progression of the exercises in the NT program were control of movements, the subjects' ability to maintain balance of the position before movements were superimposed on the position, and awareness of the position of the body in space before tolerating movements or perturbations. Exercises progressed from exercises performed on an even surface to exercises performed on different uneven surfaces and from jump exercises on 2 legs to jump exercises on 1 leg, increased hop distance for both horizontal and vertical jumps, and jumps with change in directions. The progression for the strength exercises was based on the ACSM's recommendation of dose response with increased weights and decreased number of repetitions.[14]

Based on the goals for the ST program included in this study, we probably have expected a larger strength gain in the ST group compared with the NT group. After 6 months, there were no differences between the 2 rehabilitation programs for the muscle strength tests performed. However, the NT exercises included plyometric or jump training exercises. Plyometric exercises, involving prestretching the muscle and activating the stretch-shortening cycle to produce a subsequent stronger concentric contraction, have been shown to increase muscle strength.[50] Adams et al[51] showed that the combination of plyometric exercises and traditional strength exercises such as the squat and leg press are superior in increasing muscle strength compared with only traditional ST exercises. Both traditional muscle strength exercises and plyometric exercises probably should be included in rehabilitation programs to improve muscle strength.

The significant differences between the 2 rehabilitation programs seemed to appear from 3 to 6 months after surgery, not immediately after surgery. It could also be that the first 3 months were decisive for the functional response from 3 to 6 months after surgery, but this study cannot answer that question. The exercises included in the NT program during the "running, jumping, and agility" phase, from 3 months to 6 months, seemed to result in a significantly improved subject perception of knee function compared with traditional ST exercises and the running exercises on the treadmill included in phases 3 and 4 of the ST program.

The 2 rehabilitation programs were carried out at 2 different outpatient clinics. This limitation was considered at the start of the study, but due to possible problems with communication between subjects performing 2 different rehabilitation programs at the same clinic, 2 different clinics were chosen. Furthermore, the physical therapists who administered the NT program were more familiar with those exercises and less experienced with only strength exercises. The physical therapists who were responsible for the ST program were more experienced in ST exercises, but also had some experience in NT. The physical therapists who were responsible for the 2 different programs were senior physical therapists and were all very experienced.

There also were some differences in facilities between the 2 outpatient clinics. The ST program was carried out in a larger facility with more training equipment and more ST equipment in particular compared with the clinic where the NT program was performed. This might be the reason for the significantly higher number of visits and hours spent at the outpatient clinic for the subjects in the ST group compared with the NT group. Based on the daily log sheets turned in, the adherence data indicate high adherence to both rehabilitation programs (42 visits for the NT group=88%, 58 visits for the ST group=better than 100%). However, more subjects in the NT group turned in the daily log sheets (100%) compared with the ST group (77%). Most of these factors should have indicated a better potential for the subjects in the ST group to achieve better knee function, but it was the NT group that perceived significantly improved knee function.

Some other limitations of the study also need to be addressed. The most common error made or conclusion drawn from the results of a randomized controlled trial is the type II error. Power calculations were undertaken regarding the main outcome measurement in this study, and, despite the fact that there were some dropouts at the 3- and 6-month follow-ups, a significant difference was detected for the Cincinnati Knee Score. The study did not include power calculations for the secondary outcome measures, and a significant difference was detected between the 2 groups only for the VAS for global knee function. According to Hansen et al,[30] 26 subjects should have been included to detect a significant difference between groups for the dynamic test, and 119 subjects should have been included for the static test. At the 6-month follow-up, 21 subjects in the ST group and 17 subjects in the NT group were tested on the KAT2000. The lack of differences between the 2 rehabilitation programs for the other outcome measures could be due to lack of power for these outcome measures, to similarities between the programs (these potential limitations have been addressed above), or to the fact that the other outcome measures were not sensitive enough to detect differences. Biomechanical and motion analysis studies probably should have been included to be able to answer this question. Previous motion analysis studies[4,52] have investigated changes in knee biomechanics during gait and hop tests and have demonstrated significant changes in movement patterns for perturbation training and jump training exercises.

This is, to our knowledge, the first randomized controlled trial evaluating the effect of prolonged NT exercises compared with traditional ST exercises starting after ACL reconstruction and including preoperative data on knee function. There were no differences between the 2 programs early after surgery, but a significant benefit of NT exercises was recorded by the Cincinnati Knee Score and VAS after the intervention, at the 6-month follow-up after surgery. There were no differences for any of the other outcome measures. Long-term follow-up is needed to determine whether this modest difference in favor of the NT exercises has any long-term consequences. Further research also is needed to disclose possible mechanisms for these different exercises.

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References

1 Snyder-Mackler L, Fitzgerald GK, Bartolozzi AR III, Ciccotti MG. The relationship between passive joint laxity and functional outcome after anterior cruciate ligament injury. *Am J Sports Med.* 1997;25:191–195.

2 Chmielewski TL, Rudolph KS, Snyder-Mackler L. Development of dynamic knee stability after acute ACL injury. *J Electromyogr Kinesiol.* 2002;12:267–274.

3 Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L. 1998 Basmajian Student Award Paper: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *J Electromyogr Kinesiol.* 1998;8:349–362.

4 Chmielewski TL, Hurd WJ, Rudolph KS, et al. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. *Phys Ther.* 2005;85:740–749.

5 Lewek M, Rudolph KS, Axe MJ, Snyder-Mackler L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clin Biomech (Bristol, Avon).* 2002;17:56–63.

6 Risberg MA, Lewek M, Snyder-Mackler L. A systematic review of evidence for anterior cruciate ligament rehabilitation: how much and what type? *Physical Therapy in Sport.* 2004;5:125–145.

7 Wojtys EM, Huston LJ. Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. *Am J Sports Med.* 1994;22:89–104.

8 Beard DJ, Dodd CA, Simpson AH. The effect of reconstruction on proprioception in the anterior cruciate ligament deficient knee. *Ortho Trans.* 1996;21:786.

9 Risberg MA, Holm I, Tjomsland O, et al. Changes in impairments and disabilities after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 1999;29:400–412.

10 Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. *Am J Sports Med.* 1999;27:699–706.

11 Caraffa A, Cerulli G, Projetti M, et al. Prevention of anterior cruciate ligament injuries in soccer: a prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc.* 1996;4:19–21.

12 Fitzgerald GK, Axe MJ, Snyder-Mackler L. The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. *Phys Ther.* 2000;80:128–140.

13 Ihara H, Nakayama A. Dynamic joint control training for knee ligament injuries. *Am J Sports Med.* 1986;14:309–315.

14 Liu-Ambrose T, Taunton JE, MacIntyre D, et al. The effects of proprioceptive or strength training on the neuromuscular function of the ACL reconstructed knee: a randomized clinical trial. *Scand J Med Sci Sports.* 2003;13:115–123.

15 Cooper RL, Taylor NF, Feller JA. A randomised controlled trial of proprioceptive and balance training after surgical reconstruction of the anterior cruciate ligament. *Res Sports Med.* 2005;13:217–230.

16 Noyes FR, McGinniss GH, Mooar LA. Functional disability in the anterior cruciate insufficient knee syndrome. *Sports Med.* 1984;1:278–302.

17 Shapiro ET, Richmond JC, Rockett SE, et al. The use of a generic, patient-based health assessment (SF-36) for evaluation of patients with anterior cruciate ligament injuries. *Am J Sports Med.* 1996;24:196–200.

18 Risberg MA, Holm I, Steen H, Beynnon BD. Sensitivity to changes over time for the IKDC form, the Lysholm score, and the Cincinnati knee score: a prospective study of 120 ACL reconstructed patients with 2 years follow-up. *Knee Surg Sports Traumatol Arthrosc.* 1999;7:152–159.

19 Hrubesch R, Rangger C, Reichkendler M, et al. Comparison of score evaluations and instrumented measurement after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2000;28:850–856.

20 Risberg MA, Holm I, Steen H, et al. The effect of knee bracing after anterior cruciate ligament reconstruction: a prospective, randomized study with two years' follow-up. *Am J Sports Med.* 1999;27:1–8.

21 Marx RG, Jones EC, Allen AA, et al. Reliability, validity, and responsiveness of four knee outcome scales for athletic patients. *J Bone Joint Surg Am.* 2001;83:1459–1469.

22 Price DD, McGrath PA, Rafii A, Buckingham B. The validation of visual analogue scales as ratio scale measures for chronic and experimental pain. *Pain.* 1983;17:45–56.

23 Carlsson AM. Assessment of chronic pain, I: aspects of the reliability and validity of the visual analogue scale. *Pain.* 1983;16:87–101.

24 Flandry F, Hunt JP, Terry GC, Hughston JC. Analysis of subjective knee complaints using visual analog scales. *Am J Sports Med.* 1991;19:112–118.

25 Irrgang JJ, Snyder-Mackler L, Wainner RS, et al. Development of a patient-reported measure of function of the knee. *J Bone Joint Surg Am.* 1998;80:1132–1145.

26 Hoher J, Munster A, Klein J, et al. Validation and application of a subjective knee questionnaire. *Knee Surg Sports Traumatol Arthrosc.* 1995;3:26–33.

27 Holm I. *Quantification of Muscle Strength by Isokinetic Performance* [doctoral dissertation]. Oslo, Norway: University of Oslo; 1996.

28 Kannus P, Jarvinen M, Johnson RJ, et al. Function of the quadriceps and hamstrings muscle in the knee with chronic partial deficiency of the anterior cruciate ligament. *Am J Sports Med.* 1992;20:162–168.

29 Brosky JA Jr, Nitz AJ, Malone TR, et al. Intrarater reliability of selected clinical outcome measures following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 1999;29:39–48.

30 Hansen MS, Dieckmann B, Jensen K, Jakobsen BW. The reliability of balance tests performed on the kinesthetic ability trainer (KAT 2000). *Knee Surg Sports Traumatol Arthrosc.* 2000;8:180–185.

31 Denti M, Randelli P, Lo VD, et al. Motor control performance in the lower extremity: normals vs anterior cruciate ligament reconstructed knees 5–8 years from the index surgery. *Knee Surg Sports Traumatol Arthrosc.* 2000;8:296–300.

32 Barrett DS. Proprioception and function after anterior cruciate reconstruction. *J Bone Joint Surg Br.* 1991;73:833–837.

33 Beynnon BD, Renstrom PA, Konradsen L, et al. Validation of techniques to measure knee proprioception. In: Lephart SM, Fu FH, eds. *Proprioception and Neuromuscular Control in Joint Stability.* Champaign, Ill: Human Kinetics Inc; 2000: 127–138.

34 Risberg MA, Ekeland A. Assessment of functional tests after anterior cruciate ligament surgery. *J Orthop Sports Phys Ther.* 1994;19:212–217.

35 Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am J Sports Med.* 1991; 19:513–518.

36 Booher LD, Hench KM, Worrell TW, Stikeleather J. Reliability of three single-leg hop tests. *Journal of Sport Rehabilitation.* 1993;2:165–170.

37 Risberg MA, Holm I, Ekeland A. Reliability of functional knee tests in normal athletes. *Scand J Med Sci Sports.* 1995;5:24–28.

38 Loge JH, Kaasa S. Short form 36 (SF-36) health survey: normative data from the general Norwegian population. *Scand J Soc Med.* 1998;26:250–258.

39 Loge JH, Kaasa S, Hjermstad MJ, Kvien TK. Translation and performance of the Norwegian SF-36 Health Survey in patients with rheumatoid arthritis, I: data quality, scaling assumptions, reliability, and construct validity. *J Clin Epidemiol.* 1998;51: 1069–1076.

40 Bach BR Jr, Warren RF, Flynn WM, et al. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg Am.* 1990;72:1299–1306.

41 Berry J, Kramer K, Binkley J, et al. Error estimates in novice and expert raters for the KT-1000 arthrometer. *J Orthop Sports Phys Ther.* 1999;29:49–55.

42 Risberg MA, Mork M, Jenssen HK, Holm I. Design and implementation of a neuromuscular training program following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2001;31:620–631.

43 Gray GW. *Lower Extremity Functional Profile.* Adrian, Mich: Win Marketing Inc; 1995.

44 American College of Sports Medicine Position Stand: The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. *Med Sci Sports Exerc.* 1998;30:975–991.

45 Cohen J. *Statistical Power Analysis for Behavioral Science.* 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 2005.

46 Fitzgerald GK, Axe MJ, Snyder-Mackler L. The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. *Phys Ther.* 2000;80:128–140.

47 Beard DJ, Dodd CA, Trundle HR, Simpson AH. Proprioception enhancement for anterior cruciate ligament deficiency: a prospective randomised trial of two physiotherapy regimes. *J Bone Joint Surg Br.* 1994;76:654–659.

48 Lephart SM, Pincivero DM, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med.* 1997;25: 130–137.

49 Williams GN, Chmielewski T, Rudolph K, et al. Dynamic knee stability: current theory and implications for clinicians and scientists. *J Orthop Sports Phys Ther.* 2001; 31:546–566.

50 Voight M, Tippett S. Plyometric exercises in rehabilitation. In: Prentice WE, ed. *Rehabilitation Techniques in Sport Medicine.* 2nd ed. St Louis, Mo: Mosby; 1994: 88–97.

51 Adams K, O'Shea JP, O'Shea KL, Climstein M. The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *J Strength Cond Res.* 1992;6:36–41.

52 Myer GD, Ford KR, McLean SG, Hewett TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *Am J Sports Med.* 2006;34:445–455.