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A Comprehensive Rehabilitation Program With Quadriceps Strengthening in Closed Versus Open Kinetic Chain Exercise in Patients With Anterior Cruciate Ligament Deficiency

A Randomized Clinical Trial Evaluating Dynamic Tibial Translation and Muscle Function

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Background: There is no consensus regarding the optimal rehabilitation regimen for increasing quadriceps strength after anterior cruciate ligament (ACL) injury.

Hypothesis: A comprehensive rehabilitation program supplemented with quadriceps strengthening in open kinetic chain (OKC) exercise will increase quadriceps strength and improve knee function without increasing static or dynamic sagittal tibial translation, compared with the same comprehensive rehabilitation program supplemented with quadriceps strengthening in closed kinetic chain (CKC) exercise, in patients with acute ACL deficiency.

Study Design: Randomized controlled trial; Level of evidence, 1.

Methods: Forty-two patients were tested a mean of 43 days (range, 20-96 days) after an ACL injury. Patients were randomized to rehabilitation with CKC quadriceps strengthening (11 men and 9 women) or OKC quadriceps strengthening (13 men and 9 women). Aside from these quadriceps exercises, the 2 rehabilitation programs were identical. Patients were assessed after 4 months of rehabilitation. Sagittal static translation and dynamic tibial translation were evaluated with a CA-4000 electrogoniometer. Muscle strength, jump performance, and muscle activation were also assessed. Functional outcome was evaluated by determining the Lysholm score and the Knee Injury and Osteoarthritis Outcome Score.

Results: There were no group differences in static or dynamic translation after rehabilitation. The OKC group had significantly greater isokinetic quadriceps strength after rehabilitation ($P = .009$). The hamstring strength, performance on the 1-repetition-maximum squat test, muscle activation, jump performance, and functional outcome did not differ between groups.

Conclusions: Rehabilitation with OKC quadriceps exercise led to significantly greater quadriceps strength compared with rehabilitation with CKC quadriceps exercise. Hamstring strength, static and dynamic translation, and functional outcome were similar between groups. Patients with ACL deficiency may need OKC quadriceps strengthening to regain good muscle torque.

Keywords: ACL rehabilitation; knee laxity; muscle strength; dynamic stability; electromyography

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The primary objective of rehabilitation after anterior cruciate ligament (ACL) rupture is restoration of knee function via increased neuromuscular control. This can be achieved by developing muscle strength, coordination, and proprioceptive ability. One of the major rehabilitation challenges is weakness of the quadriceps muscle.³³ Many patients with ACL injury continue to experience muscle weakness after

rehabilitation,^{8,30,49} and weakness of the quadriceps muscle is common in patients with poor functioning after the injury.^{7,14,25,27,39,50} Such patients may not undergo sufficient strength training during rehabilitation.^{23,36}

Quadriceps strengthening can be achieved through closed kinetic chain (CKC) or open kinetic chain (OKC) exercises. Closed kinetic chain exercises are modeled as closed linkages, in which a movement in 1 joint simultaneously produces movements in other joints of the extremity. Open kinetic chain exercises isolate 1 link of the kinetic chain and the distal segment is free to move.^{29,47} Because CKC exercises are considered to be safer than OKC exercises, they are frequently used and recommended for rehabilitation after ACL injury.^{1,5,10,29,38} Open kinetic chain exercises seem to produce larger anterior shear forces than do CKC exercises,^{21,51} particularly during the last 30° of knee extension.⁴⁶ In patients with ACL reconstruction, the result is substantial graft strain, which can be harmful.^{2,3,32} Patients with ACL deficiency have decreased or abolished load-bearing capacity of the ACL due to the injury, and increased shear forces can cause further loosening of the joint as a consequence of increased tension on the secondary stabilizers.^{4,44} Also, in line with the findings about larger anterior shear forces during OKC exercises, larger anterior tibial translation has been reported during OKC exercises compared with CKC exercises in these patients with ACL deficiency.¹⁸ On the other hand, application of a compressive load and muscle activation produce an anterior shift of the tibia⁴⁴ that strains the ACL during weightbearing.⁹ In addition, it has been reported that CKC and OKC exercises produce equal maximum ACL strain values.³ Recent research shows that the tibia is in a similar position during CKC and OKC activities and that the amount of translation is related to quadriceps-generated shear force.¹³ A high number of knee extensions performed during an exercise session did not affect the passive or dynamic tibial translation in healthy individuals, which indicates that strength training of quadriceps in OKC exercises may be included in a rehabilitation program.⁴² Open kinetic chain exercises are essential because they considerably task the quadriceps musculature⁴⁷; thus it is of great importance to demonstrate their effects on ACL-deficient patients.

In 1 study, patients with ACL reconstructions who trained with OKC exercises demonstrated greater anterior tibial translation than patients who trained with CKC exercises.⁵ However, there was a difference in translation only for the KT-1000 arthrometer test with maximum applied force (1.6 mm in the CKC group vs 3.3 mm in the OKC group), and no information was obtained regarding muscle strength after the rehabilitation programs. In contrast, 2 more recent studies reported that OKC exercises after ACL reconstruction did not increase laxity of the knee joint.^{23,31} Moreover, in one of these studies, the addition of OKC exercises to a CKC regimen resulted in a significant improvement of quadriceps torque and a significant increase in the number of athletes returning to their previous level of activity; among those patients who returned to their previous level of activity, patients who took part in the OKC exercises did so earlier.²³

Dynamic tibial translation is important to good functioning after ACL injury,¹⁵ but static and dynamic translation do not correlate.¹⁶ Furthermore, static tibial translation does not correlate with functional outcome after ACL reconstruction¹² or ACL deficiency,^{7,30,40} or with quadriceps or hamstring muscle strength after ACL deficiency.³⁰ In spite of this, earlier studies that examined rehabilitation including CKC exercises versus OKC exercises only investigated static translation after rehabilitation for ACL reconstruction.^{5,23,31}

The aim of this study was to compare the effects of a comprehensive rehabilitation program supplemented with quadriceps strengthening in CKC exercises with the same comprehensive rehabilitation program supplemented with quadriceps strengthening in OKC exercises, in patients with acute ACL deficiency, on static and dynamic sagittal tibial translation, muscle function, and subjective knee function. We hypothesized that a comprehensive rehabilitation program supplemented with quadriceps strengthening in OKC exercises will increase quadriceps strength and improve knee function without increasing static or dynamic sagittal tibial translation compared with the same comprehensive rehabilitation program supplemented with quadriceps strengthening in CKC exercises.

MATERIALS AND METHODS

This study was a randomized controlled trial. Ethical approval was granted by the local ethics committee (Dnr 02-374). All patients gave written informed consent before their participation.

Patients

Participants were recruited from patients visiting the orthopaedic department after knee trauma (Table 1). Patients were informed about the study and were asked to participate if they were 15 to 45 years of age and had a unilateral ACL rupture that was no more than 14 weeks old. Patients were excluded if they had additional injury or previous surgery to the lower extremities, with the exception of partial meniscal injury or minor collateral ligament injury in the injured knee joint or partial meniscectomy in the injured or contralateral knee. All ACL injuries were verified by arthroscopy or magnetic resonance imaging. According to the ordinary routines of the department, the patients were referred to rehabilitation. After completing rehabilitation, the patients were evaluated regarding the need for an ACL reconstruction. Forty-nine patients were randomly assigned to 1 of 2 treatment groups using a concealed allocation procedure (Figure 1).

Rehabilitation Programs

CKC and OKC Programs. Five physiotherapists introduced and monitored rehabilitation weekly. The rehabilitation consisted of exercises designed to increase neuromuscular control, muscle strength, and coordination and thereby functional stability. The exercises for the CKC and OKC programs are

TABLE 1
Subject Characteristics^a

| Variable | CKC (n = 20) | OKC (n = 22) | All Patients (N = 42) |
|---|-----------------|-----------------|--------------------------|
| Sex (male/female) | 11/9 | 13/9 | 24/18 |
| Mean age (range) | 27 (15-44) | 25 (16-41) | 26 (15-44) |
| Injured leg (right/left) | 11/9 | 14/8 | 25/17 |
| Method of diagnosis | | | |
| Arthroscopy before inclusion | 20 | 19 | 39 |
| Arthroscopy after posttest | 0 | 1 | 1 |
| Magnetic resonance imaging | 1 | 2 | 3 |
| ACL rupture | 20 | 22 | 42 |
| Injuries associated with the ACL rupture ^b | | | |
| Minor menisci injury | 8 | 6 | 14 |
| MCL first-degree injury | 1 | 0 | 1 |
| LCL first-degree injury | 1 | 0 | 1 |
| Cartilage injury | 2 | 1 | 3 |
| Injury | | | |
| Soccer | 9 | 12 | 21 |
| Skiing | 2 | 3 | 5 |
| Floorball | 1 | 3 | 4 |
| Basketball | 1 | 1 | 2 |
| Handball | 2 | 0 | 2 |
| Cycling | 2 | 0 | 2 |
| Other | 3 | 3 | 6 |
| Median days from injury to assessment before rehabilitation (range) | 39 (20-69) | 48 (24-96) | 43 (20-96) |
| Median days from assessment before to assessment after rehabilitation (range) | 139 (100-175) | 125 (43-169) | 132 (43-175) |

^aCKC, closed kinetic chain; OKC, open kinetic chain; ACL, anterior cruciate ligament; MCL, medial collateral ligament; LCL, lateral collateral ligament. There were no significant differences between groups ($P > .05$).

^bOne patient can have several associated injuries.

listed in Appendix 1 online (the online appendix is available in the online version of this article at <http://ajsm.sagepub.com/supplemental>). For patients in the CKC group, squatting on 1 leg was the primary quadriceps strengthening exercise. The squat was also used as a means to sufficiently load the hip extensors. For patients in the OKC group, seated knee extension on 1 leg was the primary quadriceps strengthening exercise. Standing hip extension on 1 leg was also performed. The 2 rehabilitation programs were otherwise identical. Each program was divided into 4 phases with a unique focus and goals. The goals for each rehabilitation phase and the load progression are shown in Appendix 2 online (the online appendix is available in the online version of this article at <http://ajsm.sagepub.com/supplemental>).

As tolerated, the patients gradually increased other types of exercise such as walking, cycling, and running. During the last phase of the rehabilitation program, the focus was on return to sports, and patients were encouraged to practice

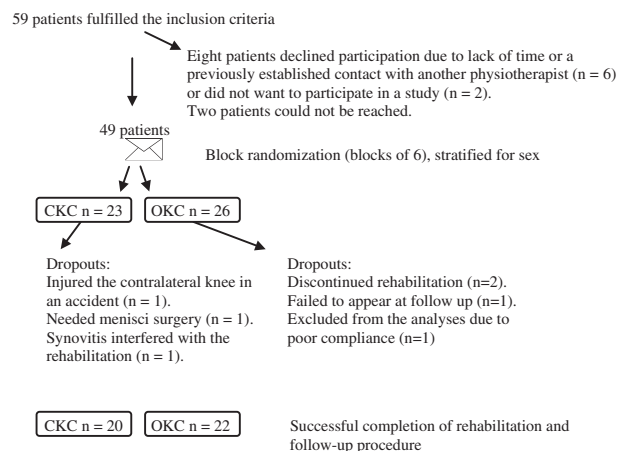


Figure 1. Patient flowchart. OKC, open kinetic chain; CKC, closed kinetic chain.

sport-specific exercises as a complement to the rehabilitation program described in online Appendix 1.

Load of the Strengthening Exercises. During the early strength-training phase, the strengthening exercises were performed with weights equivalent to 50% to 60% of 1-repetition maximum (1-RM). The uninjured leg served as a reference to determine loads for the injured leg. To achieve sufficient load, the weights were gradually increased to 70% to 80% of 1-RM (Appendix 2 online), the heaviest resistance that can be pursued for 1 complete repetition of an exercise.⁶ To set the optimal load for the exercises, a test of 1-RM⁴¹ was performed at weeks 1, 5, 9, and 13 (Appendix 2 online). The load was adjusted after each 1-RM test and, if tolerated, the load was increased by 10% at weeks 11 and 15. When application of the maximal load was considered unsuitable, a repetitions-to-failure method with submaximal load was used. The injured leg was tested only in the late-rehabilitation phases.

Progression to a more difficult form of the exercise or to a more advanced rehabilitation phase was permitted if the patient experienced no increased pain or swelling and was able to maintain postural control during the exercises. These criteria are similar to those used previously.³⁴

Exercise Frequency. Patients were asked to perform the rehabilitation program 3 times each week, each time performing 3 sets of 10 repetitions of each exercise. Compliance was monitored with self-reported exercise diaries. The patients wrote in the diary after every training session, recording all exercise. To identify patients who were optimally compliant, we applied a lower cut-off of 12 treatment sessions during rehabilitation phases 3 and 4. Subanalyses were performed with optimally compliant patients.

Assessments

Clinical Measurements. Assessments were performed before and after rehabilitation. All testing was performed barefoot. The test procedure lasted approximately 2 hours. The legs were tested in a randomized order at the assessment before the rehabilitation and in the same order at the assessment after the rehabilitation. The principal investigator (S.T.)

performed all outcome measurements and, with the exception of 7 patients whose treatment she was involved in, was blinded to the group allocation for the duration of data collection. Tests of 1-RM were performed by the physiotherapists who monitored the rehabilitation. All the data were coded during analysis, and group membership was not revealed until group comparisons were made several months later.

Swelling, measured as midpatella knee-joint circumference, was assessed using a tape measure with the patient relaxed supine on the examination table.

Passive range of motion for knee extension and flexion was measured with a standard plastic goniometer with the patient relaxed supine on the examination table. Extension was measured with a block under the patient's heel to allow for hyperextension. The arms of the goniometer were aligned with the greater trochanter and lateral malleolus, and the axis of the goniometer was placed over the knee-joint line just below the lateral femoral epicondyle.

The instrumented Lachman test was performed with the subject strapped to a special seat with the knee flexed to approximately 20°. Tibial translation was recorded with the CA-4000 (OSI Inc, Hayward, Calif) when the proximal tibia was pushed posterior and pulled anterior with a controlled force using a force handle. The total anterior-posterior translation at 90 N and 134 N in the sagittal plane is presented using the mean value of 3 repetitions.

During gait testing, the patients were instructed to walk as normally as possible at a self-chosen speed. Data from a Kistler force plate were used to identify the stance phase and we analyzed maximal anterior translation during this phase, recorded with the CA-4000. The mean electromyographic activation during the first half, second half, and the entire stance phase were analyzed.

Patients performed a single-leg squat starting from an upright position with the knee fully extended, shifting to a position of 60° of knee flexion, and returning to full knee extension, with light support. Patients wore a weight vest (10 kg for men and 8 kg for women) to increase the load of the exercise. Before rehabilitation, the test was performed for the uninjured leg only, and after rehabilitation it was performed bilaterally. The CA-4000 data for the angle of knee flexion were used to define the flexion and extension phases. Maximal anterior tibial translation and mean and maximal electromyographic activation during the flexion and extension phases were analyzed.

Patients performed 3 repetitions of maximal isokinetic 60 deg/s knee extension and flexion. Before rehabilitation, the isokinetic testing was performed for the uninjured leg only to get an initial strength value. After rehabilitation, the test was performed bilaterally. Peak torque during the flexion and extension phases was derived from the maximum torque for any of the 3 repetitions. Maximal anterior tibial translation and mean and maximal electromyographic activation were analyzed.

To compare strength and performance during a CKC exercise between the CKC and OKC groups, a test of 1-RM during a squat on 1 leg⁴¹ was performed for the uninjured leg at week 1 (the first rehabilitation session) and bilaterally at week 16 (the last rehabilitation session) (Appendix 2 online). When application of the maximal load was considered unsuitable, a repetitions-to-failure method with submaximal load was used.

Patients were assessed for their ability to perform a unilateral vertical jump with hands at their sides. Each patient stood on 1 leg on a Kistler force plate (Kistler AG, Winterthur, Switzerland) and performed 1 jump as high as possible, landing on the same foot. The time from take-off to landing was determined. In addition, each patient performed a unilateral horizontal jump for distance, with hands kept behind the back to prevent their use in generating momentum. The jump tests were performed bilaterally after the rehabilitation. The patients could refrain from these jump tests due to perceptions of instability.

Questionnaires Evaluating Subjective Knee Function and Activity Level. The Lysholm score⁴³ and the Knee Injury and Osteoarthritis Outcome Score (KOOS)³⁵ were used to evaluate subjective knee function. The Tegner score⁴³ was used to determine the level of activity. These questionnaires were answered at pre- and postrehabilitation assessments. The following supplementary questions were added at the postrehabilitation assessment: How do you experience the effect of the physiotherapy treatment (completely recovered, improved, unchanged, or worse)? Do you have fear of reinjury (yes or no)? If yes, to what extent does fear of movement prevent you from performing activities (estimated on a visual analog scale)? Do you have confidence in your knee joint (estimated on a visual analog scale)? How would you feel if you had to live with your knee problems at the current activity level (happy, satisfied, mostly satisfied, mixed feelings, mostly dissatisfied, dissatisfied, or unhappy)?

Data Acquisition. A computerized goniometer linkage (CA-4000, OSI) was used to measure the flexion angle and sagittal tibial translation. The goniometer has been described previously.¹⁸ The measurement system has satisfactory reproducibility; the mean variation between 3 consecutive dynamic measurements (gait) is 0.03 ± 0.5 mm (95% confidence interval [CI], -0.6 to 0.2). The mean variation throughout a range of motion (a squat on 2 legs, 0° to 90° to 0°) on 2 different days, was 0.73 ± 0.41 mm (95% CI, -0.51 to 1.97).¹⁷ The system also has satisfactory validity throughout a range of motion when compared with fluoroscopy.⁴⁵

The CA-4000 was zeroed at the beginning of each test with the subject supine on the examination table and the knee relaxed and fully extended. The alignment of the CA-4000 was checked repeatedly during the examination. Dynamic anterior tibial translation was calculated by subtracting the tibial position during passive extension from the tibial position during motion.¹⁸ For each test, the maximal translation was derived from each repetition, and the mean of the 3 repetitions was calculated. Data were sampled from the potentiometers by a computer at a rate of 2000 Hz.

Electromyography. Skin preparation and electrode placement were performed according to the recommendations from Surface EMG for Non-Invasive Assessment of Muscles (SENIAM).¹¹ Electromyographic activation of the vastus medialis, vastus lateralis, hamstrings, lateral part of the gastrocnemius, and the gluteus was registered using surface electrodes. Electromyographic signals were sampled at 2000 Hz by the MESPEC 4000 EMG unit system (MEGA Electronics Ltd., Kuopio, Finland).

Three repeated maximal voluntary isometric contractions (MVICs) were performed for knee extension, knee flexion, plantar flexion, and hip extension. For knee extension and

flexion, the patients sat with the knee positioned at 60° and flexed at 110°, respectively, restrained by a strap. For plantar flexion, the movement was restrained by a hand-held strap, which was attached under the plate the patient was standing on. The patient stood on 1 leg in an upright position with light balance support and raised himself/herself up on the toes as high as possible. Hip extension was performed with the patient prone on the examination table with the hip maximally extended against resistance and the knee flexed at 90°.

The peak value during MVIC served as the reference for calculating electromyographic activation. The peak electromyographic value during 100 ms was analyzed. The peak value during each exercise was normalized to the peak value during the MVIC test for each muscle (ie, relative value of 1 muscle = peak value during a movement divided by peak value during MVIC).

Muscle Torque. Torque of the quadriceps and hamstring muscles was recorded using a Biodex machine (Biodex Medical Systems Inc, Ronkonkoma, NY). The patients were secured to the chair with body straps, and the resistance pad on the measuring arm was placed at the level of the ankle joint. Before recording, some submaximal familiarization repetitions were performed.

Statistical Analysis

Sample size calculations estimated that 19 patients would be required in each group to detect a 1.5-mm difference in translation and a 10% difference in quadriceps strength between groups as significant ($\alpha = 0.05$, $\beta = 0.20$). Both between-group and within-group comparisons were made. The uninjured leg was used for ratios and comparisons with the injured leg. An independent samples *t* test was used to compare swelling, passive range of motion, translation, electromyographic data, muscle strength, and jump performance between groups. A paired samples *t* test was used to compare swelling, passive range of motion, translation, and electromyographic data before and after rehabilitation. The Tegner score and Lysholm score were analyzed using both an independent samples *t* test and the Mann-Whitney *U* test. These 2 analyses yielded similar results, and only results from the nonparametric analyses are shown. The KOOS was analyzed using the Mann-Whitney *U* test. The supplementary questions were analyzed using the χ^2 test (nominal data) and the Mann-Whitney *U* test (ordinal data). A significance level of $P < .05$ was used for all variables but for the electromyographic data, where $P < .001$ was used to control for multiple comparisons. Analyses were performed using SPSS 15.0 (SPSS Inc., Chicago, Ill) and Minitab 13 (Minitab Inc, State College, Pa).

RESULTS

Swelling and Passive Range of Motion

There were no group differences in swelling or passive range of motion before or after rehabilitation ($P > .05$, Table 2). Both groups had swelling and limitations of passive range of motion in the injured leg compared with the uninjured leg before rehabilitation ($P < .05$). After rehabilitation, knee-joint circumference of the 2 knees was equal. Statistical analysis revealed minor limitations of passive range of motion in both

TABLE 2
Performed Training Sessions, Level of Activity, Subjective Knee Function, Swelling, and Passive ROM Before and After Rehabilitation^a

| Variable | CKC (n = 20) | OKC (n = 22) | All Patients (N = 42) |
|--|-------------------|-------------------------|--------------------------|
| Median number of training sessions performed at the gym (range) | 36 (20-61) | 33 (13-63) | 34 (13-63) |
| Median Tegner score (range) | | | |
| Before injury | 7 (4-9) | 7 (4-10) | 7 (4-10) |
| After rehabilitation | 4 (4-6) | 4 (4-7) | 4 (4-7) |
| Median Lysholm score (range) | | | |
| Before rehabilitation | 62 (32-82) | 75 (51-94) ^b | 68 (32-94) |
| After rehabilitation | 94 (58-100) | 92 (64-100) | 94 (58-100) |
| Median midpatella girth difference in cm, (range) | | | |
| Before rehabilitation | 0.8 (-0.5 to 2.5) | 0.7 (-0.5 to 2.5) | 0.7 (-0.5 to 2.5) |
| After rehabilitation | 0.1 (0.0-0.5) | 0.1 (0.0-1.0) | 0.1 (0.0-1.0) |
| Median passive ROM difference before rehabilitation in deg (range) | | | |
| Extension | -5 (-24 to 0) | -6 (-23 to 0) | -5 (-24 to 0) |
| Flexion | -22 (-59 to -3) | -16 (-43 to 0) | -19 (-59 to 0) |
| Median passive ROM difference after rehabilitation in deg (range) | | | |
| Extension | -1 (-5 to 1) | -1 (-8 to 0) | -1 (-8 to 1) |
| Flexion | -1 (-7 to 4) | -2 (-8 to 1) | -2 (-8 to 4) |

^aROM, range of motion; CKC, closed kinetic chain; OKC, open kinetic chain; difference = injured leg - uninjured leg.

^bSignificant difference between groups ($P < 0.05$).

groups (mean extension and flexion deficits $\leq 2^\circ$, Table 2) that did not exceed the measurement error²² and therefore should not be of clinical importance.

Lachman Test

The Lachman test revealed no group differences in maximal total translation of the tibia for the uninjured leg, injured leg, and the ratio of injured to uninjured leg before and after rehabilitation. In both groups, there was no change in static translation of either leg after rehabilitation (Table 3).

Gait

There were no group differences in maximal anterior translation of the tibia during gait for the uninjured or injured leg before or after rehabilitation (Table 3). Moreover, the ratio of the injured to uninjured leg did not differ between groups. There was also no difference in anterior translation during

TABLE 3
Maximal Translation for the Lachman Test, Gait, Squat on 1 Leg, and Isokinetic Knee Extension at 60 deg/s Before and After Rehabilitation^a

| Measurement | Before Rehabilitation | | P value | After Rehabilitation | | P value |
|---------------------------|------------------------|------------------------|---------|------------------------|------------------------|---------|
| | CKC | OKC | | CKC | OKC | |
| Lachman 90-N | | | | | | |
| Uninjured | 4.6 ± 1.4 | 5.3 ± 1.3 | .108 | 4.8 ± 1.3 | 5.1 ± 1.3 | .606 |
| Injured | 6.3 ± 2.1 ^b | 5.9 ± 1.5 | .522 | 6.1 ± 1.7 ^b | 6.1 ± 1.9 ^b | .882 |
| Lachman 134-N | | | | | | |
| Uninjured | 5.6 ± 1.7 | 6.4 ± 1.4 | .114 | 5.9 ± 1.6 | 6.2 ± 1.6 | .610 |
| Injured | 7.8 ± 2.5 ^b | 7.7 ± 1.5 ^b | .973 | 7.8 ± 2.4 ^b | 7.6 ± 2.1 ^b | .769 |
| Gait | | | | | | |
| Uninjured | 4.2 ± 1.4 | 4.8 ± 1.7 | .215 | 4.8 ± 1.7 | 4.6 ± 1.6 | .677 |
| Injured | 4.8 ± 1.4 ^b | 4.7 ± 2.1 | .830 | 5.6 ± 1.7 ^b | 5.8 ± 2.0 ^b | .750 |
| Squat | | | | | | |
| Uninjured | 5.2 ± 1.2 | 6.2 ± 2.4 | .110 | 5.5 ± 1.3 | 5.0 ± 2.3 | .395 |
| Injured | n.p. | n.p. | | 6.1 ± 1.5 | 6.3 ± 3.4 | .766 |
| Isokinetic knee extension | | | | | | |
| Uninjured | 7.5 ± 1.9 | 8.6 ± 2.8 | .171 | 7.7 ± 1.6 | 8.1 ± 2.3 | .500 |
| Injured | n.p. | n.p. | | 9.0 ± 1.3 ^b | 9.7 ± 3.0 ^b | 0.360 |

^aCKC, closed kinetic chain; OKC, open kinetic chain; n.p., not performed. Translation is mean ± standard deviation.

^bSignificant difference between injured and uninjured leg (*P* < 0.05).

gait for the uninjured leg before versus after rehabilitation, but the injured leg demonstrated increased anterior tibial translation after rehabilitation compared with before rehabilitation in both the CKC (*P* = .011) and OKC (*P* = .044) group. After rehabilitation, there was greater anterior tibial translation in the injured leg compared with the uninjured leg in both the CKC group (*P* = .013) and the OKC group (*P* = .001) (Table 3).

There were no differences between groups in maximum or minimum knee flexion angle during gait before or after rehabilitation. Before rehabilitation, the minimum flexion angle was greater in the injured leg versus the uninjured leg in both the CKC group (6° ± 5° vs 1° ± 4°, *P* = .002) and the OKC group (5° ± 6° vs 0° ± 7°, *P* = .009). In addition, in the CKC group, the minimum flexion angle was greater in the injured leg before versus after rehabilitation (6° ± 5° vs 2° ± 5°, *P* = .025). After rehabilitation, in both groups the knee flexion angles during gait were similar on the 2 sides.

Muscle activation in the 2 groups was similar before and after rehabilitation (*P* > .001). In the CKC group, the mean activation of hamstrings of the injured leg was significantly reduced after rehabilitation (*P* = 0.001, Table 4). Also, in both groups there was a trend toward decreased mean activation of vastus lateralis in the injured leg during the entire stance phase after versus before rehabilitation (CKC group: *P* = .002; OKC group: *P* = 0.038; Table 4). In the CKC group, there was also a trend toward reduced mean activation of vastus medialis (*P* = .018) and the gastrocnemius (*P* = .052) in the injured leg after versus before rehabilitation. There were no other differences in electromyographic activation in the injured leg before versus after rehabilitation.

Single-Legged Squat

Maximal tibial translation during a single-legged squat was equal in the CKC and OKC groups for the uninjured leg before and after rehabilitation and for the injured leg after

TABLE 4
Electromyographic Activation During Gait Before and After Rehabilitation^a

| Muscle | Before Rehabilitation | | After Rehabilitation | |
|------------------|-----------------------|---------|----------------------|---------|
| | CKC | OKC | CKC | OKC |
| Vastus medialis | | | | |
| Uninjured | 14 ± 16 | 23 ± 27 | 17 ± 24 | 27 ± 38 |
| Injured | 19 ± 14 | 14 ± 11 | 10 ± 6 | 14 ± 12 |
| Vastus lateralis | | | | |
| Uninjured | 15 ± 6 | 13 ± 8 | 11 ± 5 | 11 ± 8 |
| Injured | 17 ± 6 | 15 ± 9 | 11 ± 5 | 10 ± 5 |
| Hamstrings | | | | |
| Uninjured | 8 ± 5 | 8 ± 6 | 7 ± 4 | 10 ± 9 |
| Injured | 23 ± 18 | 18 ± 16 | 7 ± 4 | 11 ± 11 |
| Gastrocnemius | | | | |
| Uninjured | 17 ± 9 | 25 ± 33 | 15 ± 9 | 19 ± 11 |
| Injured | 31 ± 29 | 27 ± 16 | 16 ± 11 | 25 ± 31 |
| Gluteus maximus | | | | |
| Uninjured | 25 ± 26 | 18 ± 11 | 21 ± 15 | 13 ± 11 |
| Injured | 18 ± 15 | 29 ± 36 | 25 ± 60 | 28 ± 35 |

^aCKC, closed kinetic chain; OKC, open kinetic chain. Activation is % of maximal voluntary isometric contraction, mean ± standard deviation.

There were no significant differences between the CKC and OKC group (*P* > .001).

rehabilitation (Table 3). In addition, the ratio of translation for the injured to uninjured leg was similar for the 2 groups.

Both groups used a similar muscular stabilizing strategy when performing the single-legged squat. There were no differences between groups in mean electromyographic activation for the uninjured leg before or after rehabilitation or for the injured leg after rehabilitation. Analysis of maximal electromyographic activation showed that the ratio of gluteus maximus activation for the injured leg to uninjured leg

during the flexion phase of the squat after rehabilitation was larger for the OKC group (CKC group: injured leg $22\% \pm 13\%$ MVIC, uninjured leg $41\% \pm 31\%$ MVIC; OKC group: $39\% \pm 29\%$ MVIC, $23\% \pm 13\%$ MVIC; $P = .001$).

Isokinetic Knee Extension and Flexion at 60 deg/s

Isokinetic testing of the uninjured leg before rehabilitation showed equal muscle strength in the CKC and OKC groups. After rehabilitation, quadriceps strength of the injured leg (expressed as a percentage of the quadriceps strength of the uninjured leg) was significantly greater in the OKC group compared to the CKC group. Hamstring strength of the injured leg (expressed as a percentage of the hamstring strength of the uninjured leg) did not differ between groups (Table 5).

There were no group differences in maximal anterior tibial translation during extension or flexion of the uninjured leg before or after rehabilitation or of the injured leg after rehabilitation. After rehabilitation, translation during the extension phase was greater for the injured leg than the uninjured leg in both the CKC group ($P = .002$) and the OKC group ($P = .031$) (Table 3).

There were no significant differences in patterns of muscle activation between groups.

1-RM Squat

In the 1-RM squat test after rehabilitation, muscle strength of the injured leg (expressed as a percentage of muscle strength in the uninjured leg) did not differ between groups (Table 5).

When 1 outlier in the OKC group was excluded, muscle strength of the injured leg decreased from $100\% \pm 27\%$ to $95\% \pm 14\%$.

Jump

There were no differences in jump performance between groups after rehabilitation (Table 5).

Subjective Knee Function and Level of Activity

Before rehabilitation, the median Lysholm score was higher in the OKC group than in the CKC group ($P = .009$). After rehabilitation, the Lysholm score indicated similar knee function in the 2 groups ($P = .826$, Table 2). Thus, the degree of improvement was greater for the CKC group ($P = .044$).

Two subscales of the KOOS indicated poorer knee function in the CKC group versus the OKC group before rehabilitation. In the subscale Function in Daily Living, the median score was 70 (range, 47-99) for the CKC group and 89 (range, 44-100) for the OKC group ($P = .031$). In the subscale Function in Sport and Recreation, the CKC group scored 5 (range, 0-80) and the OKC group scored 30 (range, 0-95) ($P = .014$). Scores on the Pain, Symptoms, and Knee-related Quality of Life subscales before rehabilitation were equal between groups. After rehabilitation, the KOOS indicated a similar functional outcome for the 2 groups; there were no group differences in scores for the subscales.

TABLE 5
Muscle Strength and Jump Performance
in the Injured Leg After Rehabilitation^a

| Test | CKC | OKC | P Value |
|---------------------------------|-------------------|-------------------|---------|
| Isokinetic knee extension | 84 ± 15 | 96 ± 14 | .009 |
| Isokinetic knee flexion | 99 ± 23 | 97 ± 15 | .764 |
| 1-RM squat | 95 ± 11 | 100 ± 26 | .525 |
| Single-legged vertical jump | 91 ± 11 (n=18) | 94 ± 15 (n=18) | .444 |
| Single-legged jump for distance | 93 ± 15 (n=18) | 96 ± 8 (n=20) | .362 |

^aCKC, closed kinetic chain; OKC, open kinetic chain; 1-RM, 1-repetition maximum. Expressed as % of muscle strength or jump performance in the uninjured leg (mean ± standard deviation).

There were no differences between groups in the Tegner score before injury (retrospective estimation at the assessment before rehabilitation) or after rehabilitation. The median activity level decreased after the injury in both groups (Table 2). Some patients planned to return to their sport and participate in team training and competition after completion of rehabilitation (15 CKC, 14 OKC), some were scheduled for ACL reconstruction (4 CKC, 7 OKC), and some decided to adjust activity to a lower level (1 CKC, 1 OKC).

There were no group differences in subjective experience of the effect of physiotherapy. In the CKC group, 2 patients felt completely recovered and 18 felt improved; in the OKC group, 5 patients felt completely recovered, 16 felt improved, and 1 felt unchanged ($P = .315$).

Fourteen patients in the CKC group and 13 patients in the OKC group expressed fear of reinjury ($P = .461$). The groups similarly estimated the extent to which fear of movement limited the performance of activities ($P = .109$). The 2 groups also expressed equal confidence in the knee joint, estimated on a visual analog scale ($P = .112$).

Satisfaction with the current level of activity did not differ between the groups ($P = .261$). Eleven patients in the CKC group and 12 patients in the OKC group reported that they were happy, satisfied, or mostly satisfied.

Subanalysis of Optimally Compliant Patients

All patients were exposed to the 2 programs' specific exercises to some extent. However, the number of training sessions performed ranged widely (Table 2). The mean number of training sessions performed was 35 for the CKC group and 33 for the OKC group ($P = .653$). Fourteen patients in the CKC group and 15 patients in the OKC group met the criteria for optimal compliance. Analyses of tibial translation and muscle strength for the optimally compliant patients produced results that were overall similar to those for the main analyses. However, the intergroup difference in quadriceps strength was larger; quadriceps strength for the injured leg (expressed as a percentage of the strength of the uninjured leg) was $80\% \pm 15\%$ for the CKC group and $99\% \pm 11\%$ for the OKC group ($P = .001$).

DISCUSSION

This study shows that a comprehensive rehabilitation program supplemented with an OKC quadriceps exercise leads to significantly greater quadriceps strength during an isokinetic test compared with the same comprehensive rehabilitation program supplemented with a CKC quadriceps exercise. In contrast, hamstring strength, static and dynamic translation, and functional outcome are similar with the 2 regimens. Isokinetic testing after rehabilitation demonstrated that the OKC quadriceps exercise was more effective than the CKC quadriceps exercise in restoring the strength of the quadriceps muscle. However, the 2 groups performed similarly during the CKC muscle strength test (squatting on 1 leg). Consistent with these findings, a previous study showed that addition of OKC quadriceps training to a CKC rehabilitation protocol for patients who underwent ACL reconstruction significantly improved quadriceps torque.²³ However, it is uncertain if the increased strength observed in that study is attributable to the specific OKC quadriceps exercises or simply to the increased quantity of quadriceps training. In the present study, we controlled for an increase in quantity of training by comparing groups receiving OKC or CKC quadriceps training and found that quadriceps strength after rehabilitation was greater in the OKC group versus the CKC group.

Functioning of the quadriceps muscle after an ACL injury seems to be a critical factor in the patient's ability to cope with the injury.⁵⁰ Consequently, it is of great importance to regain quadriceps strength after injury. Our results support the theory that OKC quadriceps training is necessary to regain good muscle torque, especially when measuring isokinetic quadriceps strength.²³ When evaluating subjective knee function and jump performance, there was no difference between groups, which indicates that both rehabilitation regimens, when performed in a well-structured fashion, were effective in restoring knee function.

Fourteen patients in the CKC group and 15 patients in the OKC group met the criteria for optimal compliance. Analyses of quadriceps strength for these optimally compliant patients showed an even larger difference between groups, strength still being greater for the OKC group. This suggests that a high level of compliance to the CKC regimen does not increase quadriceps strength and that the squat exercise is insufficient for quadriceps strengthening. However, the somewhat low compliance in some patients is a limitation of this study and should be considered when interpreting the results.

We are fairly confident that the findings are free from investigator bias. The 5 physiotherapists who monitored the rehabilitation were experienced in ACL rehabilitation and participated in the design of the rehabilitation programs. All physiotherapists were concordant in the monitoring of the programs, with respect to the guiding of the individual exercise regimen. The principal investigator who performed all outcome measurements in the laboratory was blinded to the group allocation for the great majority of the patients; it was not possible to secure a blinded test procedure for the 7 patients whose treatment she monitored, which is a limitation of the study. However,

all data were coded during analysis and the analyses were performed several months after the assessments.

At the time of the postrehabilitation assessment, most patients had begun to practice running, jumping, agility drills, and specific sports activities. However, as demonstrated by the Tegner scores, many patients had not returned to their preinjury level of activity. It has been suggested that it is appropriate to allow patients to begin sports activities when they can tolerate full-speed agility training and the specific activities of their sport and when the involved leg has a strength deficit of <15% and a single-leg jump deficit of <15%.³⁴ The mean deficit in quadriceps muscle strength during isokinetic testing was 16% for the CKC group, slightly below the recommended level, and only 4% for the OKC group. Healthy female soccer players have a difference in isokinetic knee extensor strength (60 deg/s) of 8% between the strong and weak leg.²⁸ Accordingly, the differences between the injured and the uninjured leg in the present study can be compared with these normative values of difference between limbs in uninjured individuals. Ten patients in the CKC group and 17 patients in the OKC group regained quadriceps strength of 85% in the injured leg relative to the uninjured leg; however, the number of patients was not significantly different. In spite of the somewhat poor quadriceps strength in the CKC group, most patients in both groups met the criteria necessary to return to sports.

There were no group differences for the KOOS subscales Pain or Symptoms before or after rehabilitation, an indication that the 2 groups were not differently limited by pain. Moreover, the physiotherapists who monitored the rehabilitation and followed up with the patients each week confirmed that no patients experienced patellofemoral pain. Thus, while CKC exercises are preferred in ACL rehabilitation because of a lower incidence of patellofemoral pain,⁵ a difference in patellofemoral pain was not verified in the present study. Our findings are consistent with a recent study that reported no differences in anterior knee pain in patients who participated in a CKC or an OKC training program after ACL reconstruction.²⁴

A limitation of earlier studies comparing CKC and OKC rehabilitation programs is that only static translation was assessed.^{5,23,31} Static translation does not correlate with functional activity,^{7,30} functional knee score,¹² or muscle strength.³⁰ Therefore, it is essential to evaluate dynamic translation as well. Dynamic translation is dependent on static translation and neuromuscular control. In the present study, we report both the total anterior-posterior translation at 90 N and 134 N in the sagittal plane and the maximal anterior translation during the exercises. Neither static nor dynamic translation differed between groups. Closed kinetic chain exercises cause smaller translation than do OKC exercises¹⁸; this can be accounted for by higher joint compression forces that decrease anterior-posterior translation during CKC exercise.^{44,46} However, weightbearing causes anterior positioning of the tibia, and activation of the quadriceps and gastrocnemius muscles increases joint compression and stiffness during CKC exercises. In patients with ACL deficiency, this results in an anterior position of the tibia when secondary restraints are

involved.^{17,44} Beynnon et al³ found that CKC and OKC exercises produce similar ACL strain forces. In the present study, the tibial translation did not differ between groups, which can be interpreted to mean that the secondary restraints in the knee joint were similarly affected after completion of rehabilitation. These results are consistent with previous studies reporting that CKC and OKC exercises can both be safely implemented in an ACL rehabilitation program.^{23,26,36}

In both groups, static translation was equal before and after rehabilitation. However, in the injured leg, translation during gait increased after rehabilitation. Dynamic translation is dependent on neuromuscular control, and we used electromyography to investigate the basis for potential differences in dynamic translation. Reduced electromyographic activation after rehabilitation is 1 conceivable explanation for the increased translation during gait. The reduction in hamstring activation, however, was only significant in the CKC group. Moreover, there was a tendency toward reduced activation of the vastus lateralis in both groups after the rehabilitation. In the CKC group, there was also a tendency toward reduced activation of the vastus medialis and the gastrocnemius in the injured leg after rehabilitation. Cocontraction leads to increased joint compression and, as a consequence, stiffening of the joint, which increases joint stability in the anterior position.^{17,19,20} In the present study, before rehabilitation, patients did not extend the injured knee to the same extent as the uninjured knee, an indication that they were using a joint-stiffening strategy during gait. After rehabilitation, the movement pattern of the injured knee was partially restored, and the flexion angle during gait was similar for the injured and uninjured knees. The patients used the joint-stiffening strategy and reduced the dynamic tibial translation before rehabilitation, whereas after rehabilitation range of motion and electromyographic activation in the injured leg was normalized (ie, similar to that in the uninjured leg), and the dynamic translation increased. Consistent with this idea, we recently showed that an individual with ACL deficiency used smaller dynamic tibial translation 8 weeks after injury as compared with before the injury, indicating use of a joint-stiffening strategy in the early period after injury.¹⁹ Increased cocontraction^{37,48} and reduced knee motion³⁷ have been observed in ACL-deficient individuals who are categorized as noncopers (ie, individuals who do not function well after the ACL injury). Conversely, copers exhibit no symptoms of knee instability and demonstrate a joint range of motion and pattern of muscle activation similar to uninjured individuals.³⁷ In the present study, after the rehabilitation, when the patients had a better knee function, they used a joint range of motion and muscle activation pattern that was more normalized, and the translation during gait increased, as compared with before rehabilitation. The results are in line with a recent study that showed that patients who function well after an ACL injury used greater anterior translation in the injured knee than in their uninjured knee during gait, while patients with poor knee function had smaller anterior translation, probably as a result of stiffening of the joint to avoid functional instability.¹⁵

In conclusion, rehabilitation with OKC quadriceps exercise led to significantly better quadriceps strength compared with CKC rehabilitation. In contrast, hamstring strength, static and dynamic translation, and functional outcome were similar between groups. Patients with ACL deficiency may need OKC quadriceps strengthening to regain good muscle torque.

Many patients with ACL deficiency undergo ACL reconstruction. Remaining muscle weakness after completed rehabilitation is common. Therefore, in the future it would be interesting to perform a similar study on patients with an ACL reconstruction.

The clinical recommendation from the present study is that quadriceps strengthening in OKC should be included in rehabilitation programs after ACL deficiency to achieve good quadriceps strength. The exercise does not reduce knee-joint stability in ACL-deficient patients.

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