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Closed kinetic chain alone compared to combined open and closed kinetic chain exercises for quadriceps strengthening after anterior cruciate ligament reconstruction with respect to return to sports: a prospective matched follow-up study

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Abstract Rehabilitation after anterior cruciate ligament (ACL) reconstruction has focused over the past decade on closed kinetic chain (CKC) exercises due to presumably less strain on the graft than with isokinetic open kinetic chain exercises (OKC); however, recent reports suggest that there are only minor differences in ACL strain values between some CKC and OKC exercises. We studied anterior knee laxity, thigh muscle torque, and return to pre-injury sports level in 44 patients with unilateral ACL; group 1 carried out quadriceps strengthening only with CKC while group 2 trained with CKC plus OKC exercises starting from week 6 after surgery. Anterior knee laxity was determined with a KT-1000 arthrometer; isokinetic concentric and eccentric quadriceps and hamstring muscle torque were studied with a Kin-Com dynamometer before and 6 months after surgery. At an average of 31 months after surgery the patients answered a questionnaire regarding their current knee function and physical activity/sports to determine the extent and timing of

their recovery. No significant differences in anterior knee laxity were noted between the groups 6 months postsurgery. Patients in group 2 increased their quadriceps torque significantly more than those in group 1, but no differences were found in hamstring torque between the groups. A significantly higher number of patients in group 2 ($n=12$) than in group 1 ($n=5$) returned to sports at the same level as before the injury ($P<0.05$). Patients from group 2 who returned to sports at the same level did so 2 months earlier than those in group 1. Thus the addition of OKC quadriceps training after ACL reconstruction results in a significantly better improvement in quadriceps torque without reducing knee joint stability at 6 months and also leads to a significantly higher number of athletes returning to their previous activity earlier and at the same level as before injury.

Keywords ACL reconstruction · ACL rehabilitation · Anterior knee laxity · Closed kinetic chain · Isokinetic open kinetic chain

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Introduction

Anterior cruciate ligament (ACL) rupture is one of the most common and most serious traumatic injuries among physically active individuals [8]. The Swedish company Folksam, which insures most Swedish athletes, reports

that ACL injury entails the longest disability period, leads to the highest percentage of permanent sports disability, and is the most expensive injury for the company and for society [8].

There is still no consensus regarding the optimal rehabilitation program following ACL reconstruction except for early motion, which was pointed out some 25 years

ago by Eriksson [7] and has since been confirmed by Noyes et al. [18]. The importance of hamstring strengthening during the first postoperative weeks after ACL reconstruction has been advocated [26]. Some authors express concern that active quadriceps strengthening during the last 30° of knee extension may be harmful because it produces substantial ACL graft strain [2, 3, 20]. Several years ago studies carried out by Shelbourne and Nitz [22], Shelbourne et al. [23], and Pässler et al. [19] suggested that ACL-reconstructed patients should be treated with closed kinetic chain (CKC) exercises rather than open kinetic chain exercises (OKC) in order to protect the ACL graft. Bynum et al. [4] maintained that CKC exercises should be used exclusively after ACL reconstruction. Over the past decade CKC training has become the standard means for treating patients after ACL reconstruction. However, Beynon et al. [3] have recently reported that there were only minor differences in ACL strain values between CKC and OKC exercises. In our experience, patients treated only with CKC exercises have problems regaining sufficient quadriceps torque to return to sports after a 6 months rehabilitation period. Several authors also report low quadriceps muscle output after ACL injuries [9, 10, 14, 15, 21, 25].

The primary aim of the present investigation was to evaluate the effect of CKC quadriceps rehabilitation versus the same program with addition of OKC exercises following ACL reconstruction on anterior knee laxity and isokinetic muscle torque. A secondary aim was to determine whether this leads to differences in knee function and the ability to return to sporting activities.

Patients and methods

Patients

Forty-four men and women aged 18–40 years with their first-ever unilateral ACL injury and a healthy contralateral leg participated in this study, approved by the Karolinska Hospital ethics committee. Patients with a previous serious knee injury or a concomitant other injury that might influence the rehabilitation were excluded. No acute ACL injuries were included. All patients except one woman were athletes in various sports such as soccer ($n=22$), floor ball ($n=4$), team handball ($n=2$), basketball ($n=2$), volleyball ($n=1$ patient), bandy on ice ($n=2$), downhill skiing ($n=3$), gymnastics ($n=3$), karate ($n=1$ patient), thaiboxing ($n=1$ patient), and motorcross ($n=2$). All underwent ACL reconstruction using a bone patellar tendon bone graft and were operated on by a standardized arthroscopy-assisted technique using the central one-third of the patellar tendon, 10–11 mm wide. The surgical procedures were performed as a one-incision technique by three highly experienced ACL surgeons.

The patients were randomized into two groups, each with 22 patients. Those in group 1 trained only with CKC quadriceps exercises; this group included 17 men aged 19–40 years (25.7 ± 4.8) and 5 women aged 17–22 years (19.4 ± 2.5). Those in group 2 were treated with the same CKC exercises but from week 6 after surgery with the addition of OKC for the quadriceps muscle; in this group there were 17 men aged 18–39 years (25.4 ± 5.4) and 5 women aged 18–21 years (19.0 ± 1.4). Each patient was matched to another pa-

tient for age, gender, and type and level of physical activity/sports. The one woman who was not an athlete was randomized into group 2 and was matched to a patient in group 1 with a low physical activity level.

KT-1000 measurement

Anterior knee laxity was determined with the KT-1000 arthrometer (MEDmetric, San Diego, Calif., USA) [5, 17] in all patients before surgery and 6 months postoperatively by one and the same examiner, who postoperatively was unaware of the preoperative KT-1000 result. Since the original report by Daniel et al. [5] in 1985 many other authors have studied and found a good reproducibility of the KT-1000 [1, 24, 30]. In the present study we performed the test in 30° knee flexion with the patient in supine position on a bench with a foot support to constrain external tibial rotation equally on both sides. The joint line was marked, and the patients were instructed to totally relax their thigh muscles. This was carefully checked by the examiner before the test. The contralateral healthy leg was tested first and then the ACL injured leg. The value of the maximum manual test was used for statistical analyses [1].

Isokinetic measurement

A Kin-Com dynamometer (Chattecx, Chattanooga, Tenn., USA) [11] was used for measuring quadriceps and hamstring torque within the range of 10°–90° knee flexion. Both concentric and eccentric actions were measured at angular velocities of 30, 120, and 240°/s. Patients sat with the thigh supported, with 90° hip flexion, a support for the low back, a fixation girdle around the pelvis, and the arms folded. The resistance pad was placed just above the malleoli. Determinations at each velocity were obtained while superimposing the last record on the preceding ones. The highest observed amplitude was accepted in order to exclude measurements at submaximal effort [13]. Torque values were corrected for gravitational force [13]. For comparisons of voluntary strength the average torque within a movement range of 20°–80° of knee flexion from at least three determinations was used. The isokinetic measurements were performed both preoperatively and 6 months postoperatively by the same examiner.

Rehabilitation protocol

Rehabilitation started the first day after the ACL reconstruction. The rehabilitation protocol consisted of traditional items such as range of motion and flexibility training, proprioceptive and balance training, CKC exercises, and hamstring training (Table 1). The two groups followed the same rehabilitation protocol during the first 5 weeks. From week 6 group 2 also received isokinetic concentric and eccentric quadriceps exercises, initially within 90°–40° of knee flexion, which over 6 weeks was gradually increased to 90°–10° of knee flexion (Table 2). Group 2 continued with these OKC quadriceps exercises during the entire rehabilitation period. Otherwise the two groups continued the same rehabilitation program for 6 months postoperatively. Both groups performed the rehabilitation at the hospital under supervision of the same physical therapist throughout the entire rehabilitation time.

Follow-up evaluation

A questionnaire regarding knee function and satisfaction, physical activity and/or sports participation was answered by all patients, on average 31.0 ± 9.7 months after surgery. The patients were asked to judge their knee function at that time using the following four

Table 1 Our standard rehabilitation protocol for both groups followed after ACL reconstruction

Time	Exercises
0–2 weeks	Passive knee extension exercises Active knee flexion exercises Electrical muscle stimulation (if unable to contract quadriceps and/or hamstring)
2–6 weeks, add:	Patella mobilization (if needed) Gait training Closed kinetic chain exercises (quadriceps and hamstrings) Hamstring training (gradually isokinetically) Proprioceptive and balance training Stationary biking (when 100° of knee flexion)
6–12 weeks, add:	Functional exercises (stair walking, skip the rope, “skating” on a slide board)
3–4 months, add:	Jogging straight ahead on an even surface
4–6 months, add:	Jogging and running on an uneven surface Jogging with turns 90°, 180°, 360° Cutting with 45° changes of direction Acceleration and deceleration running Sport-specific exercises

Table 2 Our isokinetic open kinetic chain quadriceps training protocol that was added from week 6 in group 2 after ACL reconstruction

Week	ROM (°)	Angular velocity (°/s)		Reps
		Concentric	Eccentric	
6	90–40	120	30	50
7	90–40	120	30	80
8	90–30	120	30	60
		90	90	60
9	90–30	120	30	90
		90	90	80
10	90–20	120	30	70
		90	90	70
		30	120	70
11	90–20	120	30	80
		90	90	80
		30	120	90
12	90–10	120	30	80
		90	90	70
		30	120	80
		240	240	70

scale parameters: excellent, good, fair, and poor. They were also asked to report their knee satisfaction at that time using the following four scale parameters: very satisfied, satisfied, not fully satisfied, and dissatisfied. Furthermore, they were asked whether they had returned to sports, and if so, they were asked whether they returned at the same or a lower level than before their injury, and at what time they started their sporting activities after surgery. If they

had not returned to sports or had returned to a lower level and/or to a less knee demanding sports they were asked for what reason.

Statistics

Data were summarized with standard descriptive statistics (mean value \pm SD). In cases of severely skewed distributions the median \pm IQR/2 was used. For approximately normally distributed variables, differences between groups and changes over time were analyzed by analysis of variance for repeated measurements (group \times leg \times time) with leg and time as repeated measurements. Differences between groups in the outcome variables (global rating of outcome and number of patients who had returned to sports at the same level) were analyzed by the χ^2 method (Fisher's exact test, if the expected number of subjects in a cell was ≥ 5). A significance level of $P < 0.05$ on a two-tailed test was applied.

Results

Anterior knee laxity

In group 2 the KT-1000 measurements of anterior knee laxity differed 7.8 mm preoperatively and 1.2 mm postoperatively between the ACL reconstructed and healthy contralateral legs. The corresponding values in group 1 were 7.8 mm preoperatively and 1.7 mm postoperatively. These differences between the groups were not statistically significant (Table 3).

Isokinetic muscle torque

Table 4 presents the proportional side-to-side differences (injured vs. healthy leg) in quadriceps and hamstring torque preoperatively and 6 months postoperatively. The patients in group 2 had increased their quadriceps torque significantly more than those in group 1 6 months after surgery (Table 5). After 6 months no significant differences in concentric or in eccentric hamstring torque were found between the groups.

Clinical outcome: return to sports

Of the 22 patients who strengthened their quadriceps with both OKC and CKC exercises (group 2) 12 returned to sports at the same level as before the injury, after a me-

Table 3 Mean values \pm SD of anterior knee laxity (mm), KT-1000-max, preoperatively and 6 months postoperatively in the ACL injured and healthy contralateral knee ($n=22$ in each group)

	CKC only		CKC + OKC	
	Preop	Postop	Preop	Postop
Injured knee	15.5 \pm 3.6	9.1 \pm 3.2	15.6 \pm 2.9	8.5 \pm 2.2
Healthy knee	7.7 \pm 1.9	7.4 \pm 2.1	7.8 \pm 2.4	7.3 \pm 2.4

Table 4 Mean values (%) of the side-to-side differences (injured vs. healthy leg) of the isokinetic concentric and eccentric quadriceps and hamstring torque within 20°–80° of knee flexion, preoperatively and 6 months postoperatively ($n=22$ in each group)

	CKC only				CKC + OKC			
	Quadriceps		Hamstrings		Quadriceps		Hamstrings	
	Preop	Postop	Preop	Postop	Preop	Postop	Preop	Postop
30°/s								
Concentric	76.4	65.7	89.1	92.8	81.2	78.8	89.2	96.9
Eccentric	77.3	65.7	88.5	86.6	84.9	83.2	87.7	96.0
120°/s								
Concentric	84.4	72.2	91.8	96.6	87.6	79.7	95.8	103.3
Eccentric	82.9	69.8	90.4	94.4	87.2	79.5	89.2	102.1
240°/s								
Concentric	85.9	75.6	91.7	88.7	89.0	82.6	96.2	104.4
Eccentric	90.7	70.4	89.7	93.5	87.1	79.8	92.8	100.2

Table 5 Mean values \pm SD of isokinetic concentric and eccentric quadriceps torque (Nm) within 20°–80° of knee flexion of both legs 6 months postoperatively ($n=22$ in each group)

	CKC only		CKC + OKC		P^a
	Injured leg	Healthy leg	Injured leg	Healthy leg	
30°/s					
Concentric	114.3 \pm 35.8	174.0 \pm 44.0	129.1 \pm 42.7	163.9 \pm 49.3	<0.01
Eccentric	144.7 \pm 39.9	220.3 \pm 58.0	157.5 \pm 53.4	189.4 \pm 55.0	<0.001
120°/s					
Concentric	102.5 \pm 27.3	141.9 \pm 34.1	110.4 \pm 32.5	138.6 \pm 36.4	<0.05
Eccentric	146.5 \pm 36.5	210.0 \pm 50.3	155.5 \pm 52.3	195.7 \pm 56.5	<0.01
240°/s					
Concentric	83.2 \pm 22.8	110.0 \pm 27.6	86.1 \pm 24.2	104.3 \pm 25.1	<0.07
Eccentric	143.4 \pm 37.9	203.7 \pm 52.3	150.0 \pm 47.9	188.0 \pm 51.2	<0.02

^aSide to side differences (injured vs. healthy leg) between the groups is reported

dian of 7.5 \pm 1.0 months. Eight patients had reduced their activity level and/or changed to a less knee demanding sport due to impaired knee function in three patients, social and family reasons in three, and the fear of reinjuring the knee in two. One patient did not return to any type of sport due to a new knee injury of the contralateral leg. One patient was not physically active either before or after ACL reconstruction.

Of the 22 patients who strengthened their quadriceps with only CKC exercises (group 1) five returned to sports at the same level as before the injury, at a median of 9.5 \pm 3.0 months postoperatively. Fifteen patients had reduced their activity level and/or changed to a less knee demanding sport due to impaired knee function in ten patients, social and family reasons in four, and the fear of reinjuring the knee in one. Two patients did not return to any type of physical activity after surgery due to a fracture of the lower extremity in one patient, and one patient did not respond to the questionnaire.

A higher proportion of patients in group 2 returned to sports at the same level as before the ACL injury than in group 1 ($P<0.05$).

Subjective rating of knee function and knee satisfaction

Ratings of knee function and knee satisfaction averaged 31.0 \pm 9.7 months postsurgery in both groups. There were no significant differences between the groups with regard to subjective knee function or knee satisfaction. The reports of knee function and knee satisfaction in group 2 were excellent or very satisfied in nine patients, good or satisfied in 11, and fair or not fully satisfied in two. The reports of knee function and knee satisfaction in group 1 were excellent or very satisfied in six patients, good or satisfied in 11, fair or not fully satisfied in four, and poor or dissatisfied in one.

Discussion

We studied knee joint stability and thigh muscle torque, comparing clinical outcome in terms of knee function and return to sports after CKC quadriceps training and after a CKC plus OKC quadriceps training in ACL reconstructed patients. There was no difference between the treatments with regard to knee joint stability. This indicates that isokinetic OKC quadriceps training starting 6 weeks postoperatively within a range of 90°–40° of knee flexion does

not harm the ACL reconstruction. However, a longer follow-up would be needed to confirm this definitively. We know from several animal studies (e.g., [27, 29]) that some strain on a healing ligament produces a stronger ligament, although we do not know how much strain is excessive. Both the OKC and the CKC exercises performed in the present study were carefully controlled. Therefore they probably did not lead to excessive strain on the graft. Irrgang et al. [16] have reported good results with a controlled OKC training. It is our belief, in agreement with Bynum et al. [4], that unrestricted OKC exercises might place too much strain on the ACL graft. Therefore we strongly recommend the OKC training to be performed under controlled conditions and to start from week 6 after the ACL reconstruction.

As in earlier studies (e.g., [7, 9]) we found the quadriceps muscle very vulnerable in patients undergoing ACL reconstructions. In spite of a 6-month intensive rehabilitation program our patients did not fully regain the quadriceps torque of their reconstructed leg. However, the patients who trained their quadriceps with CKC plus OKC exercises showed a significantly greater improvement in their quadriceps torque than those who carried out only CKC exercises. This was most evident in eccentric muscle torque and is probably due to the use of isokinetic training, which allows specific eccentric loading. Our results indicate that the quadriceps needs OKC training to regain good muscle torque. This is also in agreement with Davies [6], who has pointed out the importance of additional OKC exercises to restore total muscle function.

Twelve of the 22 patients who followed a quadriceps strengthening program with both OKC and CKC exercises (group 2) and only five of 22 who trained with only CKC (group 1) returned to the same sports and activity level postsurgery as before they were injured. Quadriceps torque may play a role in return to sports, since the patients in group 2 showed greater improvement of their quadriceps than those in group 1. Furthermore, the side-to-side differences 6 months postsurgery were less in group 2 than in group 1, meaning that the patients in group 2 had recovered their quadriceps strength better. The patients in group 2 also returned to sports 2 months earlier than those in group 1 without altered knee joint stability. This is in agreement with the findings of Glasgow et al. [12], who compared two groups, one early and one late returning to sports 2–6 months and 7–14 months

after ACL reconstruction. An early return to physical activity did not predispose the patients to a less satisfactory clinical outcome [12]. Our isokinetic OKC training protocol for quadriceps strengthening evidently improved the group 2 patients' possibility of returning to sports earlier and at the same level as before they were injured. This means that there probably is a need for additional OKC quadriceps training to be able to return to high level of sports after ACL reconstruction. We recommend OKC training.

Patients evaluated their knee function on average 31 months after ACL reconstruction and answered whether they were satisfied with their knee function. The two groups were equally satisfied. However, it should be pointed out that 15 of 22 patients in group 1 and only 8 of 22 in group 2 had reduced their activity level and/or changed to a less knee demanding sport. Furthermore, 10 of 15 of group 1 patients and only 3 of 8 of group 2 patients did so because of impaired knee function. Since the two groups of patients were operated on with the same standardized technique and rehabilitated by the same physical therapist, this indicates that CKC exercises alone are not sufficient for a good outcome in terms of return to physical activity after ACL reconstruction. This is in agreement with Snyder-Mackler et al. [25], who concluded that CKC exercises alone do not adequately stimulate the quadriceps muscle to normal knee function. On the basis of this study, we agree with Wilk et al. [28] that a rehabilitation program should combine various exercises including both OKC and CKC, and that a mixture of the two best facilitates the patient's return to full, unrestricted physical activity.

Conclusion

We conclude that a combination of CKC and OKC quadriceps exercises is better than strengthening the quadriceps with only CKC exercises after ACL reconstruction, since this leads to significantly better quadriceps muscle torque and significantly earlier return to the original sports at the same level as prior to injury without compromising knee joint stability.

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References

1. Anderson AF, Snyder RB, Federspiel CF, Lipscomb AB (1992) Instrumented evaluation of knee laxity: a comparison of five arthrometers. *Am J Sports Med* 20:135–140
2. Beynon BD, Fleming B, Johnson R, Renström P, Nichols C (1995) Anterior cruciate ligament strain behavior during rehabilitation exercises in-vivo. *Am J Sports Med* 23:24–34
3. Beynon BD, Johnson RJ, Fleming BC, Stankewich CJ, Renström PA, Nichols CE (1997) The strain behavior of the anterior cruciate ligament during squatting and active flexion-extension. A comparison of an open and a closed kinetic chain exercise. *Am J Sports Med* 25:823–829

4. Bynum EB, Barrack RL, Alexander AH (1995) Open versus closed chain kinetic exercises after anterior cruciate ligament reconstruction. A prospective randomized study. *Am J Sports Med* 23:401–406
5. Daniel DM, Stone ML, Sachs R, Malcom L (1985) Instrumented measurement of anterior knee laxity in patients with acute anterior cruciate ligament disruption. *Am J Sports Med* 13:401–407
6. Davies GJ (1995) The need for critical thinking in rehabilitation. *J Sport Rehabil* 4:1–22
7. Eriksson E (1976) Sports injuries of the knee ligaments – their diagnosis treatment and rehabilitation. *Med Sci Sports* 8:133–144
8. Eriksson E, Svensson L-I, Kam San T, Valentin A (1996) Late results and sequelae after soccer. In: Garrett WE (ed) *The U.S. soccer sports medicine book*. Williams & Wilkins, Baltimore, pp 374–382
9. Elmqvist L-G (1988) Chronic anterior cruciate ligament tear. Knee function and knee extensor muscle size, morphology and function before and after surgical reconstruction. Thesis, Umeå University, Umeå, Sweden
10. Engström B, Gornitzka J, Johansson C, Wredmark T (1993) Knee function after anterior cruciate ligament ruptures treated conservatively. *Int Orthop* 17:208–213
11. Farrell M, Richards JG (1986) Analysis of the reliability and validity of the kinetic communicator exercise device. *Med Sci Sports Exerc* 18:44–49
12. Glasgow SG, Gabriel JP, Sapaga AA, Glasgow MT, Torg JS (1993) The effect of early versus late return to vigorous activities on the outcome of anterior cruciate ligament reconstruction. *Am J Sports Med* 21:243–248
13. Gransberg L, Knutsson E (1983) Determination of dynamic muscle strength in man with acceleration controlled isokinetic movements. *Acta Physiol Scand* 119:317–320
14. Harter RA, Osternig LR, Standifer BA (1990) Isokinetic evaluation of quadriceps and hamstrings symmetry following anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil* 71:465–468
15. Ikeda H (1993) Isokinetic torque of quadriceps in patients with untreated anterior cruciate ligament injury of the knee joint. *Nippon Seikeigeka Gakkai Zasshi* 67:826–835
16. Irrgang JJ (1994) ACL rehabilitation in non operative and post operative management. *Clin Sports Med* 12:797–813
17. Malcom LL, Daniel DM, Stone ML, Sachs R (1985) The measurement of anterior knee laxity after ACL reconstructive surgery. *Clin Orthop* 196:35–41
18. Noyes FR, Mangine RE, Barber S (1987) Early knee motion after open and arthroscopic anterior cruciate ligament reconstruction. *Am J Sports Med* 15:149–160
19. Pässler HH, Shelbourne KD (1995) Biological, biomechanical and clinical approaches to the follow-up treatment of ligament surgery in the knee. *Sports Exerc Injury* 1:83–95
20. Renström P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH (1986) Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med* 14:83–87
21. Seto JI, Orofino AS, Morrissey MC, Medeiros JM, Mason WJ (1988) Assessment of quadriceps/hamstring strength, knee ligament stability, functional and sports activity levels five years after anterior cruciate ligament reconstruction. *Am J Sports Med* 16:170–180
22. Shelbourne KD, Nitz P (1992) Accelerated rehabilitation after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 15:256–264
23. Shelbourne KD, Klootwyk TE, DeCarlo MS (1992) Update on accelerated rehabilitation after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 15:303–308
24. Sherman OH, Markolf KL, Ferkel RD (1987) Measurements of anterior laxity in normal and anterior cruciate absent knees with two instrumented test devices. *Clin Orthop* 215:156–161
25. Snyder-Mackler L, Delitto A, Bailey SI, Stralka SW (1995) Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am* 77:1166–1173
26. Solomonow M, Baratta R, Zhou BH, Shoji H, Bose W, Beck C, Dámbrosia R (1987) The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med* 15:207–213
27. Tipton CM, James SL, Mergner W, Tcheng TK (1970) Influence of exercise on the strength of the medial collateral knee ligaments of dogs. *Am J Physiol* 218:894–901
28. Wilk KE, Zheng N, Fleisig GS, Andrews JR, Clancy WG (1997) Kinetic chain exercise: implications for the anterior cruciate ligament patient. *J Sport Rehabil* 6:125–143
29. Woo SLY, Gomez MA, Sites TJ, Newton PO, Orlando CA, Akeson WH (1987) The biomechanical and morphological changes in the medial collateral ligament of the rabbit after immobilization and remobilization. *J Bone Joint Surg Am* 69:1200–1211
30. Wroble RR, Van Ginkel LA, Grood ES, Noyes FR, Schaffer BL (1990) Repeatability of the KT-1000 arthrometer in a normal population. *Am J Sports Med* 18:396–399