KNEE EXTENSOR MUSCLE FUNCTION BEFORE AND AFTER RECONSTRUCTION OF ANTERIOR CRUCIATE LIGAMENT TEAR

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ABSTRACT. Knee extensor performance, in 17 subjects with chronic anterior cruciate ligament (ACL) tear, was investigated preoperatively and on four different occasions postoperatively, using isokinetic measurements and electromyography of single maximum and repetitive manoeuvres. Preoperatively maximum mechanical output was comparatively low (injured leg), deteriorating further by 50 % at fourteen weeks postoperatively. Endurance also falls markedly. Thereafter knee-extensor performance improved successively, mostly during intensive training (14–20 weeks postoperatively) irrespective of the training programme used. After one year, maximum performance was still unequal but the injured leg had achieved the "normal" preoperative noninjured value. Fatiguability/endurance level improved over preoperative values. Muscular work/integrated EMG was stable while EMG/t increased. Twenty weeks postoperatively quadriceps area was decreased to 69 %, cf. noninjured control. The early postoperative loss of performance was evidently caused by loss of muscle mass. Neuromuscular relearning appears to be a sizable factor in later recovery. Isokinetic training does not offer any specific advantage in the early muscular rehabilitation after ACL reconstruction.

Key words: knee joint; exercise therapy; ligaments, articular; electromyography; muscle contraction; muscular atrophy.

Mechanical output of the knee extensors at single maximum manoeuvres has been described in patients with chronic anterior cruciate ligament (ACL) tear both before (13, 25) and up to about 8 years after reconstruction of the ligament (1, 21, 22). In our previous report (13), we found that before reconstruction of the ACL there was a reduced active range of motion and mechanical output, i.e. peak torque (PT) and contraction work (CW). Furthermore, the decrease in mechanical output was not primarily dependent upon muscular hypotrophy or morphological changes. Further investigations (3) indicated that changes in the nervous afferent inflow from the knee joint could explain this reduction in performance, probably through a decreased neuromuscular drive.

Fatiguability/endurance level (14) of the knee extensors in patients with ACL tears have hitherto not been thoroughly investigated, either before or after surgical reconstruction. Different postoperative regimens such as casting and carefully increased motion exercises (19), early mobilization with hinged cast (22) or brace (18), progressive resistance exercises (8) and isokinetic exercises (26) have been used to train this category of patients. The advantage of isokinetic training over progressive resistance training has also been shown by some workers (7), although others found no difference between various training programmes (8).

The aim of this study was to analyze the mechanical output of the knee extensors at single maximum isokinetic contractions (90°/s), and especially the fatiguability of these muscles up to 100 repetitive contractions (90°/s), before, and on four different occasions during one year of physical rehabilitation, after ACL-reconstruction. The analysis used several isokinetic dimensions (peak torque, contraction work and manoeuvre time—active range of motion) and electromyographic techniques. Furthermore, the investigation was designed to compare the short and long-term influences of two different postoperative training programmes, used during weeks 14 through 19 postoperatively, on these parameters and on quadriceps muscle size.

MATERIAL AND METHODS

Seventeen patients, who had had reconstruction of the anterior cruciate ligament performed by one orthopaedic surgeon (L-G E) according to the method described by Marshall et al. (16), were included. Postoperatively, the operated leg was immobilized for six weeks in a cylinder cast, with the knee in either 30° (9 patients) or 70° of flexion (8 patients). Isometric quadriceps exercises were not allowed during this time. For the following 2 weeks a removable splint was substituted for the cast and isometric and motion exercises carefully introduced. During the next six weeks they all followed the same training programme, now with a derotation brace. The programme consisted of 1 further week of isometric quadriceps exercises, 3 weeks of dynamic quadriceps exercises against the weight of the limb and 2 weeks of progressive resistance exercises. Dynamic hamstring exercises against the resistance of a rubber band started 3 weeks after the removal of the cast. Crutches, with partial weight-bearing, were allowed during this time. Fourteen weeks after the operation, the patients were allocated either to a combination of isometric and progressive resistance (C) or to an isokinetic (I) training programme, both of which continued for six weeks.

Group C comprised seven patients (2 females and 5 males) with a mean age at operation of 25 years (range 17–38) and group I ten patients (2 females and 8 males) with a mean age at operation of 24 years (range 19–33).

The C-group followed a programme ordinarily used at the Department of Orthopaedics. The programme started with isometric quadriceps exercises and dynamic hamstring exercises in the sitting position against the resistance of a rubber band. Each contraction was made for 6 s with a 3 s rest interval between each contraction. A total of 10 contractions was performed twice with rest interval, for both muscle groups, three times per day, each day for six weeks. The dynamic knee extensions performed once daily, started with a load corresponding to 50% of one repetition maximum (RM) (2) for three sets of 10 contractions with 5 min resting period. The RM was evaluated weekly and the load successfully increased to 80% with 12 contractions. The patients were originally instructed by a physiotherapist who also supervised the training once a week.

The I-group used a Cybex isokinetic dynamometer (Lumex Inc, New York, USA) for training the operated leg. Under the supervision of the physiotherapist, warming-up exercises, without appreciable resistance, were performed in the dynamometer for five minutes and were followed by the training. The subjects lay supine on a plinth, with the knees hanging over the plinth at approximately 110 degrees flexion and hips approximately 20 degrees flexed. The training programme consisted of 10 maximum knee extensions at a preset velocity of angular motion of 90°/s. This procedure was repeated three times at one minute intervals between each set of 10 extensions. After approximately 10 min rest, another three sets of 10 extensions were performed. Hence, the total number of maximum knee extensions were 60 per training session. The patients trained three days a week for six weeks. All manoeuvres were displayed on an *X–Y* storage oscilloscope (Tektronix, Oregon, USA). The patients were instructed to view the screen throughout the training session, thus providing visual feed-back. The visualization also allowed the physiotherapist to ascertain that the subjects cooperated adequately.

As the training started relatively early after surgical intervention, the patients were specifically asked at each training session if they had pain in the operated knee. All patients denied the occurrence of painful sensations. There was no incidence of local inflammatory reactions, such as swelling or tendinitis around the knee, or any increased instability during the training period.

After the 17th week swimming and bicycling were allowed and used by almost all patients. After the 19th week, isokinetic training was discontinued and both the C- and I-groups used the same programme of progressive resistance and coordination exercises. After 34 weeks the patients were allowed to jog, provided that the quadriceps peak torque was 65–75% of that of the nonoperated leg. More advanced training programmes, including sports exercises, were instituted at approximately 40 weeks postoperatively in order to prepare the patient for return to full activity in work or sports. The total training time was approximately one year.

Isokinetic performance

The mechanical output of single maximum contractions of the knee extensors of both legs at 90°/s was registered using the same, regularly calibrated, isokinetic equipment that was used for the training. The 90°/s velocity of angular motion was chosen, as the optimal torque production may decrease markedly at isokinetic contractions exceeding one second (20). Isokinetic measurements were performed preoperatively (test I), and at 14 (II), 20 (III), 34 (IV) and 52 weeks (V) postoperatively. The patients performed three maximum knee extensions. The manoeuvre at which they reached the greatest peak torque was used for further analysis. Peak torque (measured in Nm) and manoeuvre time (s), which equals active range of movement (ROM), were recorded using a digital printer. Contraction work ($J=\square\times\int_0^{\Delta t} M dt$, where $\square$ is angular velocity in radians/s, M is torque and t is manoeuvre time) was computed. The technical details of the experimental setup have been described previously (5).

For repetitive contractions (fatiguability/endurance test) the chosen velocity of angular motion was 90°/s. Only the operated knee was tested. The patients were instructed and encouraged throughout the test to accomplish maximum force throughout the duration of each contraction, and to choose and maintain a comfortable knee extension frequency. The test was continued until 100 knee extensions, or until feelings of exhaustion made further performance impossible.

In the analysis of the fatiguability/endurance tests, CW-values for the initial level of performance (mean of contractions 1–5), slope of decline (linear regression of contractions 6–25), end of slope (mean of contractions 25–27), endurance level (mean of contractions 50–75), and level of performance at the end of the test (mean of contractions 96–100) were used (14).

On the different test occasions, results from a maximum of 17 and a minimum of 13 patients were recorded (Table I); the variation usually occurring because some patients declined to come for testing (particularly during the summer). Therefore the performance (CW) at each test was related to the result obtained at test I from the same patient.

Electromyographic (EMG) recordings

In both single maximum contraction and endurance tests (Table I) EMG-signals were obtained from the three su-

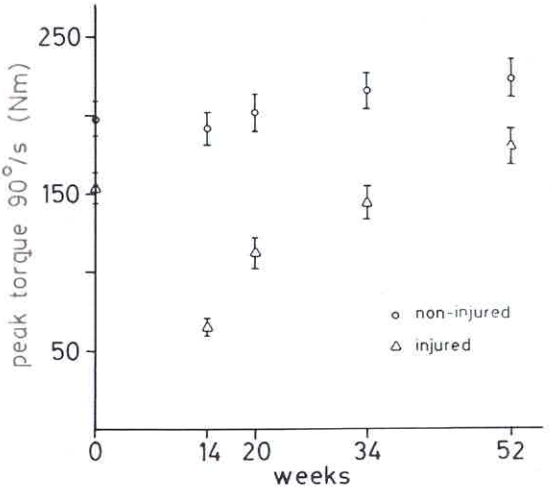

Fig. 1. Peak torque (PT) of m. quadriceps of both the injured and non-injured legs in 17 patients with ACL reconstruction at single maximum contractions (90°/s) preoperatively and at 14, 20, 34 and 52 weeks postoperatively. Significant differences ($p<0.01$) were found between the two legs at all tests.

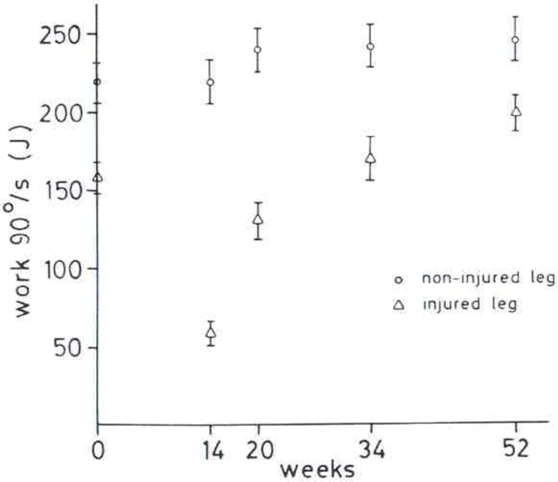

Fig. 2. Contraction work (CW) of m. quadriceps of both injured and non-injured legs in 17 patients with ACL reconstruction at single maximum contractions (90°/s) preoperatively and at 14, 20, 34 and 52 weeks postoperatively. Significant differences ($p<0.01$) were found between the two legs at all tests.

perficial parts of the m. quadriceps of the operated leg by using surface electrodes. In a few cases not all three muscle recordings were reliable and the results had to be disregarded. (This is the reason for the discrepancy between the number of patients participating in the isokinetic recordings and in the EMG recordings.) The signals were full-wave rectified, low-pass filtered and integrated, and the results were summed (iEMG, cf. 5).

Measurements of muscle cross-sectional areas (CSA) of the thigh

Computerized tomographic examinations were made using a Siemens Somatom 2 scanner, at 20 cm proximal to the knee joint line on both legs, preoperatively and 20 weeks postoperatively. Muscle tissue was defined to have an attenuation between 20 and 90 Hounsfield units (cf. 13) and the areas of the quadriceps muscles were measured and analyzed using the statistical programme of the scanner.

Statistics

Results presented in the following text and in the tables are mean values and standard errors of the mean. For comparison of data Wilcoxon's nonparametric tests were used (24). Correlation coefficients (r) were calculated by the method of least squares. The chosen level of significance was $p<0.05$.

RESULTS

Isokinetic performance

For most measurements there were no significant differences between the I- and C-groups. Hence, if not otherwise stated, the results given include the total number of patients at each test.

Single maximum contractions

The PT of the noninjured leg for all subjects increased significantly, in relation to test I, throughout tests III (5%), IV (10%) and V (14%) (Fig. 1).

Table I. *Number of patients with complete isokinetic (single (s) and repetitive (r) contractions) and EMG (obtained from both vasti and from rectus femoris during single (s) and repetitive (r) contractions) tests at the different time intervals: I = preoperative (week 0); II = 14 weeks postoperatively; III = 20 weeks postoperatively; IV = 34 weeks postoperatively and V = 52 weeks postoperatively*

	Number of patients		
	Isokinetic	EMG	
Test	s=r	s	r
I	16	15	14
II	16	10	11
III	17	16	16
IV	13	13	13
V	14	13	14

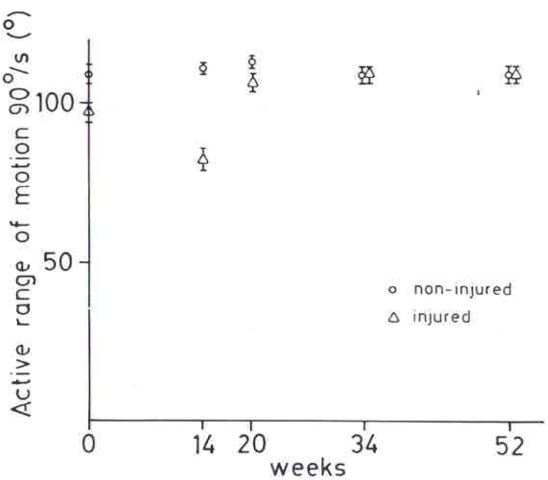

Fig. 3. Active range of motion (ROM) of both injured and non-injured legs in 17 patients with ACL reconstruction at single maximum contractions (90°/s) preoperatively and at 14, 20, 34 and 52 weeks postoperatively. Significant differences ($p<0.05$–0.01) were noted between the two legs at the first three tests but not at the last two.

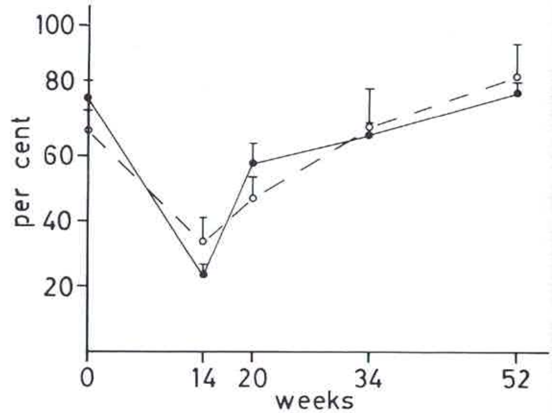

Fig. 4. Relative (per cent of non-injured leg) isokinetic contraction work at 90°/s for m. quadriceps of the injured leg in 17 patients with ACL reconstruction. Patients were trained either with an isokinetic training programme (●—●) or with a programme combining isometric and progressive resistance training (○—○). Measurements were made preoperatively and at 14, 20, 34, and 52 weeks postoperatively. No significant differences were noted between the results of the two training programmes at any of the tests.

The increases were similar for both I- and C-groups. Also CW in the noninjured leg increased significantly by 14%, 7% and 14% at tests III, IV and V, respectively (Fig. 2). The relatively greatest increase in CW was seen for the C-group. The mean ROM of the noninjured knee (Fig. 3) had only small and insignificant alterations throughout tests II-V.

At the preoperative test the mechanical output was significantly lower in the injured than the non-injured limb (79% and 73% for PT and CW, respectively). In comparison with test I a reduction of 56% for PT and 60% for CW occurred at the earliest postoperative (II) test (Table II). Six weeks later at the test III, however, CW was not significantly different from the preoperative level, while PT was still 26% reduced. At test IV, both parameters were statistically inseparable from test I, whereas at test V CW, but not PT, was significantly greater. At this time, which was at the end of the total training period, the PT and CW of the injured leg were

Table II. *Relative values (per cent of test I-injured leg) of single maximum contraction tests II, III, IV and V for peak torque (PT), contraction work (CW), range of motion (ROM) and iEMG corrected for differences in ROM (iEMG/t)*

Test	PT	CW	ROM	iEMG/t
II	44*	40*	85*	90
III	74*	86	110*	108
IV	97	111	112	145
V	126	130*	115*	134

* denotes a significant difference between each value and the value of test I.

Table III. *Peak torque (PT), contraction work (CW) and active range of motion (ROM) at 90°/s of tests II, III, IV and V in comparison with test I for single maximum contraction tests*

Differentiation has been made for the two training groups: isokinetic (I) and combination of isometric and progressive resistance (C) (for details see text). sh = significantly higher values, sl = significantly lower values and ns = no significant difference between the values of each test and test I

Test	PT I/C	CW I/C	ROM I/C
II	sl/sl	sl/sl	sl/ns
III	sl/sl	sl/ns	ns/sh
IV	ns/ns	ns/ns	ns/ns
V	ns/ns	ns/ns	ns/ns

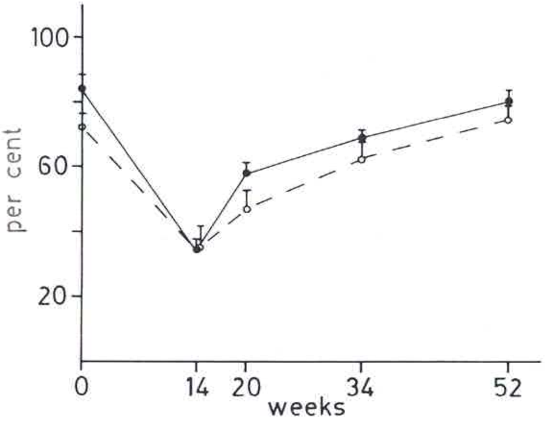

Fig. 5. Relative (per cent of non-injured leg) isokinetic peak torque at 90°/s for m. quadriceps of the injured leg in 17 patients with ACL reconstruction. Patients were trained either with an isokinetic training programme (●—●) or with a programme combining isometric and progressive resistance training (○—○). Measurements were made preoperatively and at 14, 20, 34, and 52 weeks postoperatively. No significant differences were noted between the results of the two training programmes at any of the tests.

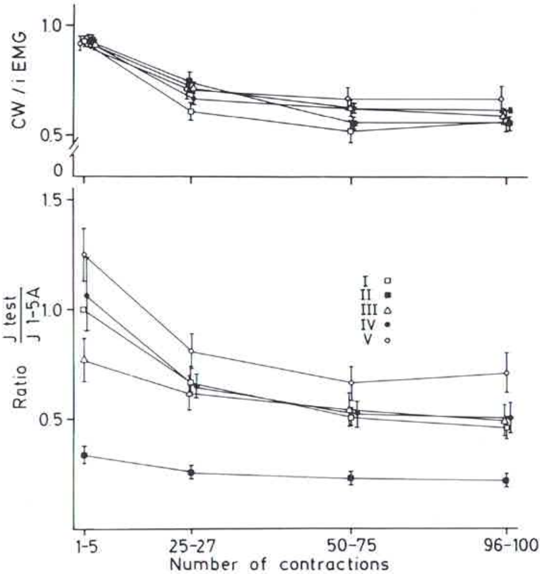

Fig. 6. Knee extensor electrical efficiency, i.e. CW/iEMG (upper diagram) and relative contraction work measured in relation to the first 5 contractions of the preoperative test (lower diagram) during fatiguability/endurance tests in 17 patients with ACL reconstruction. Tests were performed preoperatively and at 14, 20, 34, and 52 weeks postoperatively. For statistics see text.

statistically inseparable from those of the noninjured leg at test I. However, the mechanical output was still significantly lower (83% and 81% for PT and CW, respectively) than that of the noninjured leg at test V.

The active range of motion (ROM) was significantly lower at test II than at test I, but significantly higher at tests III and V (Table II). As shown in Table III, the decrease in ROM at test II was mainly caused by a significant loss of ROM in the I-group.

During the 6 week training period between tests II and III, significant increases in mechanical output occurred for both the I- and C-groups. The increase was significantly greater in the I-group than for the C-group for CW (Fig. 4) but not for PT (Fig. 5). The absolute values on the different test occasions did, however, not differ significantly. The few differences between the two groups at tests II and III, as compared with the preoperative values, were to the advantage of the C-group (Table III).

Fatiguability and endurance

At the different points of measurement relative CW was not significantly different between tests I and IV (Fig. 6). In contrast, at all points of measurements, the values obtained at test II were significantly lower than the preoperative test values (ranging between 34% and 48% of the preoperative levels). At test III, only the initial level of performance (contractions 1–5) was significantly lower than at tests I and IV. In subsequent contractions levels at all three tests (I, III, IV) were similar. Moreover, with the exception for values obtained for contractions 25–27, the patients performed significantly better at the end of physical rehabilitation (test V) than preoperatively with levels ranging between 121 to 154%. However, the value of test V for contractions 25–27 was also considerably increased (121%), but this did not achieve statistical significance.

As can also be seen in Fig. 6, the most marked decrease was during the first 25 contractions, termed the fatigue phase (cf. 4, 14), particularly during tests I, IV and V. However, this decrease was rather small at the earliest postoperative test (II). Thus, compared with the preoperative fatigue phase the patients were relatively less fatiguable at tests II and III but similarly fatiguable after 34

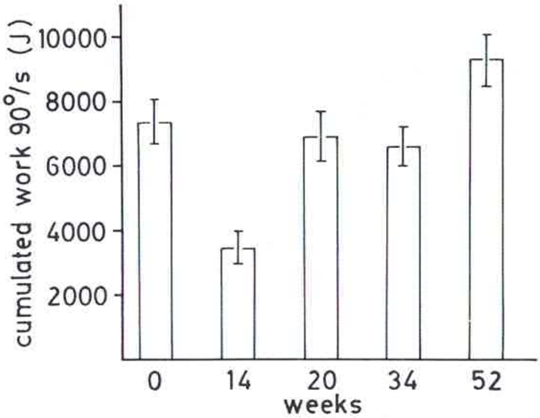

Fig. 7. Cumulated work during fatiguability/endurance tests of the knee extensors of the injured leg in patients with ACL reconstruction measured preoperatively (16 patients) and at 14 (16), 20 (17), 34 (13) and 52 (14) weeks postoperatively. Values at 14 and 52 weeks postoperatively differed significantly ($p<0.05$–0.01) from the others.

weeks (tests IV and V). As CW is the product of torque production and manoeuvre time (and hence ROM) we also calculated the slope of decline in ROM for contractions 6–25. This was identical at all tests. Therefore the differences in CW during the fatigue phase of tests II and III were due to decrease in torque production. Slight but significant decreases in level of performance were seen after the fatigue phase, up to the final contractions, for both tests I and III. At tests II, IV and V the patients reached a steady-state level, termed the endurance level (cf. 4, 14), after 60 contractions.

The dependency of CW upon both torque production and ROM motivated further analyses which are given in Table IV. In test II at the two first measuring points (contractions 1–5 and 25–27), both the peak torque and ROM were low in relation to test I after which only peak torque was low. The initial low value of CW at test III in comparison with test I appears to be caused only by lowered peak torque, while the relatively high value of CW throughout test V, was initially caused mainly by increased ROM and thereafter by increased torque production.

Another way of expressing muscular performance over time is to sum all work performed by a subject (9). The mean cumulated work performed at the different tests is given in Fig. 7. The decrease at test II of 50% and increase at test V of 33% were statistically significant.

Electromyographic recordings

The electromyographic values of the injured leg obtained for the different single maximum tests, normalized for differences in ROM (iEMG/t) and related to the preoperative value (test I) are given in Table II. At tests IV and V the values did not differ significantly from the preoperative value of the noninjured leg. The electrical efficiency (CW/iEMG) differed negligibly between and throughout all fatiguability/endurance tests (Fig. 6).

Cross-sectional areas (CSA)

Preoperatively the CSA of the quadriceps of the injured leg was 95% of that of the noninjured leg. At test III this CSA had reduced to 69%. There was no significant correlation between relative CSA of the quadriceps (per cent of the noninjured leg) and relative PT and CW preoperatively. Twenty weeks later relative CSA was not only significantly associated with relative PT ($r=0.77$) but also with relative CW ($r=0.52$).

DISCUSSION

The principal findings of this investigation of patients undergoing Marshall's reconstruction of the ACL (16) are as follows:

Fourteen weeks postoperatively. Maximum quadriceps femoris isokinetic torque production, measured as peak torque (PT) or as contraction work (CW), was significantly decreased from already lower than normal values. The considerably decreased torque production was also evident during repetitive (up to 100) knee extensions.

Table IV. *Peak torque (PT) and range of motion (ROM) at 90°/s of the various intervals of contractions of endurance tests II–V in comparison with test I*

sl = significantly lower, sh = significantly higher and ns = no significant difference between each test and test I

Test	Intervals of contraction 1–5 PT/ROM	25–27 PT/ROM	50–75 PT/ROM	96–100 PT/ROM
II	sl/sl	sl/sl	sl/ns	sl/ns
III	sl/ns	sl/ns	ns/ns	ns/ns
IV	ns/ns	ns/ns	ns/ns	ns/ns
V	ns/sh	ns/sh	sh/ns	sh/ns

From 14 weeks to one year postoperatively. The postoperative decrease in maximum mechanical output was regained. The majority of this increase, back to normal levels occurred during the intense 6-weeks training period. At this time significant relationships were found between relative PT and CW and relative CSA of the qudriceps. After one year of continued physical rehabilitation the maximum performance was statistically inseparable from that of the noninjured leg preoperatively. However, the noninjured leg performance also increased during the year while the two legs still exhibit a performance difference at one year. Fatiguability, endurance level and cumulated work were, in general, regained after 20 weeks, and at one year postoperatively they surpassed the preoperative values. All gains were largely independent of mode of training (isokinetic vs. isometric and progressive resistance), during the 14–20 weeks postoperative period.

IEMG, normalized for ROM, an expression of the mean number of muscle fibres activated during the specific manoeuvre time, had increased by 45% 8 months after operation and by 34% at the one year follow-up, although both nonsignificantly. During the whole observation period the electrical efficiency (CW/iEMG), an expression of output/input balance, was quite stable.

The maximum isokinetic knee extensor performance of the noninjured leg was slightly, but significantly, increased after 20 weeks postoperatively.

In a previous study (13) we demonstrated that preoperative maximum isokinetic quadriceps performance in patients with a chronic tear of the ACL was significantly decreased in the injured leg compared with the noninjured. There was a concomitant slight decrease in quadriceps cross-sectional area, but no major signs of muscle abnormality seen with light microscope. In these ACL deficient patients there was no correlation between maximum torque production and muscle cross-sectional area. Electromyographic studies (3) suggested that a major factor for the torque decrease was reduced central nervous drive, particularly for the m. rectus femoris. This reduced drive was tentatively explained by reduced afferent flow knee-joint receptors.

The very marked reduction of mechanical output 14 weeks after ACL-reconstruction cannot be explained by the concomitant slight reduction in ROM. As the iEMG/t was only slightly reduced, further deficient central nervous drive can hardly be blamed for the decreased output. Moreover, as gauged by the very stable output/input balance (CW/iEMG) during all fatiguability/endurance tests, if appears that the muscle fibres per se function normally as they did preoperatively (3). At least at 20 weeks postoperatively loss of quadriceps muscle mass must be blamed for the greater reduction of mechanical output. This is supported by a detailed morphological study of these patients (to be published). It is also essentially in accordance with the opinion of Sargeant (23) but disagrees with that of other workers (8, 15).

By one year post-operatively the maximum isokinetic output of the injured leg had not only regained preoperative values but even equalled the performance of the noninjured leg preoperatively. However, at each postoperative test the noninjured leg was superior to the injured leg, i.e. the noninjured leg had improved over the normal preoperative values. This happened irrespective of the mode of intensive training used and raises several interesting issues.

Firstly, although maximum isokinetic output was never equal in both legs at every given point of time, it was sufficient to bring the fatiguability and endurance measures of the injured leg up to those observed in male elite orienteers, at least during 100 repetitions (11). Comparison with other elite athletes also shows that the fatiguability and endurance level values of our patients injured legs at one year follow-up were similar to those obtained by marathon runners, although lower than the values obtained by athletes with a high demand for explosive force, such as icehockey players and sprinters (12, 14).

Secondly, this investigation did not demonstrate the advantage of either of the rigidly structured training programmes applied. In fact, we do not even know if we have simply demonstrated the natural cause of postoperative events, as we have not been able to locate any investigation including either no training or nonspecific training. Such an investigation may be unethical, but it might also contribute to clarify the value, if any, of training programmes. One investigation of the quadriceps muscle in patients with old ACL tears, by both light and electron microscopy, has actually suggested that there is no scientific rationale for selective rehabilitation of either Type I or Type II muscle fibres in patients with chronic instability of the ACL (6). The greater increase in CW in the I-group than the C-group in the 14–20 week period could simply be a bias introduced by the identical training/testing method. We did not, however, find any difference in absolute values after training, which is consistent with the findings of Ingemann-Hansen and Halkjær-Kristensen (8).

According to Thomee et al. (26), the average increase after slow (60°/s) and faster (180°/s) isokinetic training after ACL-surgery was 35% and 50%, respectively. The only explanation we can offer for the greater effect of training observed in this investigation (cf. Figs. 4–5), is that Thomee et al. (26) generally commenced training much later (6 months, range 3–12 months, postoperatively) than did our patients (14 weeks postoperatively). Thus, their patients may have gained more strength prior to training and therefore obtained less improvement from training.

Finally the significant increase in isokinetic performance of the noninjured *and nontrained* leg at the 20th postoperative week is in agreement with some authors (7, 8, 10, 17) but disagrees with others (26). This increase could be explained both by cross-transfer (8, 10, 17) and/or by increased level of activity reflecting a preoperative relative contralateral disuse (8). Clinically, it is obvious that postoperative comparison of the mechanical output of the injured and noninjured legs does not show when the injured leg achieves a performance level designated as "normal".

It is generally accepted that heavy resistance training produces an increase in muscle strength (2, 10). This is sometimes associated with increased protein synthesis leading to hypertrophy of muscle fibres (15), and is one way of increasing the mechanical output of a muscle or muscle group. However, it has also been demonstrated that during the early stages (first four weeks) of training, increase in strength is mostly a result of neuromuscular learning, while muscular hypertrophy is the major factor for later gains in performance (17). Unfortunately, this investigation was not designed to study CSA over the full one year period. However, it appears that neuromuscular learning (cf. the increase and eventual normalization of the iEMG/t of maximum quadriceps performance and the improvement of fatiguability and endurance level at 34–52 weeks postoperatively) is also an important factor for late recovery after reconstruction of ACL tears. Owing to a number of incomplete iEMG registrations, we consider our conclusions on the results in this area to be somewhat tentative. However, the stable relation between output and input appears to support our interpretations. As demonstrated by the PT and CW values, neuro-muscular learning, was still not sufficient to normalize the mechanical output during single maximum manoeuvres.

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