Electrical Stimulation of the Thigh Muscles After Reconstruction of the Anterior Cruciate Ligament

EFFECTS OF ELECTRICALLY ELICITED CONTRACTION OF THE QUADRICEPS FEMORIS AND HAMSTRING MUSCLES ON GAIT AND ON STRENGTH OF THE THIGH MUSCLES*

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ABSTRACT: **The effects of neuromuscular electrical stimulation on the strength of the thigh muscles and on gait were examined in ten patients after reconstruction of the anterior cruciate ligament. The patients were randomly assigned to one of two treatment groups: neuromuscular electrical stimulation and volitional exercise, or volitional exercise alone. A four-week course of electrically elicited co-contraction of the thigh muscles resulted in significant attenuation of the characteristic loss of strength of the quadriceps as compared with volitional exercise. There was no significant difference between groups in any measure of performance of the hamstring muscles. In the group that received neuromuscular electrical stimulation, the values for cadence, walking velocity, stance time of the involved limb, and flexion-excursion of the knee during stance were significantly different from those of the volitional exercise group. Flexion-excursion of the knee during stance was directly and significantly correlated with strength of the quadriceps femoris muscle. Flexion of the knee during stance was qualitatively different in the involved extremity as compared with the uninvolved extremity in all patients. There is a rapid flexion of the knee at weight acceptance that is maintained throughout stance and probably reflects stabilization of the joint by muscular coactivation to compensate for weakness of the quadriceps. The patients who received neuromuscular electrical stimulation had stronger quadriceps muscles and more normal gait patterns than those in the volitional exercise group.**

The treatment of patients after reconstruction of the anterior cruciate ligament has changed drastically in the past decade[42,46,48]. Currently, the treatment regimen usually consists of early active motion of the knee joint and strengthening of the thigh muscles, as these patients have marked weakness of the quadriceps femoris[2,55,64]. However, exercise of the quadriceps femoris may cause increased tension on the graft when the muscles are contracted in isolation, resulting in ligamentous laxity[1,24,26,51]. This presents a dilemma to the clinician, since exercises to improve the strength of the quadriceps, which is necessary to recovery, may provoke the very instability of the joint that the operation was intended to correct.

Co-contraction of the hamstrings and quadriceps has been suggested as a means of ameliorating the effects of isolated contraction of the quadriceps on the graft while allowing strengthening of the muscles[28]. Unfortunately, it is extremely difficult to teach a patient to perform co-contraction at an intensity sufficient to provide overload to the muscles. In an effort to counter this motor-learning problem, investigators have begun to use electrically elicited co-contraction of the quadriceps and hamstrings in the rehabilitation of these patients[11]. Neuromuscular electrical stimulation has been shown to improve the torque-generating capability of the quadriceps femoris after operations on the knee ligaments[11,18,20,22]. Preliminary evidence suggests that neuromuscular electrical stimulation may be more effective in increasing isometric strength of these muscles than volitional co-contraction and that this type of training may be applicable to other types of contractions (concentric, eccentric, and isokinetic)[11,34,45,57]. The ability to generalize gains in strength from neuromuscular electrical stimulation to other types of contractions may result in more carryover to function than occurs with volitional strength-training. Electrically elicited co-contraction has been shown to decrease strain on the graft and to increase strength of the periarticular muscles in studies of both humans and primates[11,28]. Strength, however, is only one component of recovery. It is not clear if this mode of training alters functional outcomes.

Decreased strength of the thigh muscles has been shown to be associated with decreased walking velocity, single-limb support time, and stride length in patients who have a torn anterior cruciate ligament and have had transfer of the pes anserinus[50]. In similar studies of arthritic patients, decreased flexion of the knee during stance was correlated with weakness of the quadriceps[61]. The relationship between

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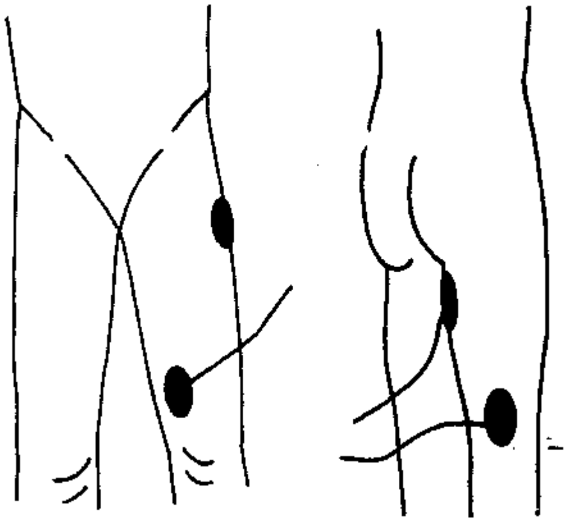

FIG. 1

Schematic drawings showing placement of the electrodes for neuromuscular electrical stimulation of the quadriceps femoris and hamstring muscles.

weak muscles of the thigh and diminished flexion of the knee during the stance phase of gait has also been suggested by biomechanical models of gait[50,58,68,69]. It is therefore reasonable to expect that increases in muscle strength caused by electrically elicited contractions will similarly improve gait.

In the assessment of the merits of a given rehabilitation program, the costs as well as the benefits associated with each program must be considered. Volitional exercises can be carried out by the patient at home or with minimum supervision in a clinical setting. Treatment with neuromuscular electrical stimulation, however, is clinic based, more labor intensive, and therefore more costly. In order for such a rehabilitation program to be both cost and labor effective, it must demonstrate its ability to allow earlier or easier protected return to function, in addition to the provision of increased range of motion and increased muscle strength.

The purpose of this investigation was to ascertain the effects of electrically elicited co-contraction of the thigh muscles on several parameters of gait and on isokinetic performance of muscles in patients who had had reconstruction of the anterior cruciate ligament. To determine whether training with neuromuscular electrical stimulation can alter functional outcomes, a comparison was made of the characteristics of gait between involved and uninvolved extremities, after exercise with volitional or electrically elicited co-contractions. Flexion of the knee during stance as well as cadence, velocity, and stance time were measured to assess functional recovery early in the rehabilitation of these patients.

Clinical Material

Ten patients who had recently had reconstruction of the anterior cruciate ligament were randomly assigned to one of two treatment groups: neuromuscular electrical stimulation and volitional exercise (five patients) or volitional exercise alone (five patients). The ages of the patients ranged from eighteen to twenty-eight years. There were four women and six men. Eight patients had grafts of the tendon of the semitendinosus muscle augmented by the Kennedy ligament-augmentation device (3M, St. Paul, Minnesota). In the remaining two patients, the central one-third of the patellar ligament was used as a bone-ligament-bone free graft. All patients were thoroughly familiarized with the purposes and procedures of the study and gave informed consent before they were admitted to the study. The investigation was approved by the Boston University Charles River Campus Institutional Review Board.

Procedures and Instrumentation

Training Program

The patients in the neuromuscular electrical-stimulation group were treated three days each week from the third through the sixth postoperative week. The patient's postoperative orthotic device was removed, and four electrodes were connected to the same circuit and placed to provide simultaneous, forceful contractions of the quadriceps and hamstring muscles with minimum discomfort. For stimulation of the quadriceps femoris, electrodes were placed distally over the vastus medialis and proximally over the vastus lateralis. For stimulation of the hamstrings, the electrodes were placed distally over the short head of the biceps femoris and proximally over the muscle bellies of the medial hamstrings (Fig. 1). The patients were positioned sitting, with the knee in 60 degrees of flexion. An isokinetic dynamometer (Cybex II; Lumex, Ronkonkoma, New York), was fixed in the isometric mode, and the thigh and ankle cuffs were secured. The electrical stimulator was then turned on, and the amplitude of the current was increased until the maximum tolerable contraction was attained. Treatment consisted of fifteen maximum, electrically elicited co-contractions of the quadriceps femoris and hamstring muscles during each session.

The clinical electrical stimulator that was used in this study (VersaStim 380; Electro-Med Health Industries, Miami, Florida) delivers a 2500-hertz (pulse duration, 400 microseconds) triangular, alternating current at a 50 per cent duty cycle of seventy-five bursts per second. On-off times were fifteen seconds on (inclusive of a three-second ramp) and fifty seconds off. Tolerance to electrical stimulation generally increases as patients become accustomed to it. Therefore, the amplitude of the current was increased from contraction to contraction, as tolerated, during each treatment. Torque output was monitored with the dynamometer to ensure that no net knee-extension torque was produced by the electrically elicited contraction.

Both groups of patients were instructed in volitional co-contraction of the muscles of the thigh. On the days when the patients did not receive treatment, they exercised volitionally. The patients were asked to assume a position of 60 to 90 degrees of flexion of the knee and to perform fifteen co-contractions (fifteen-second contraction, fifty-second rest) twice each day, seven days each week. They were

TABLE I

GRAVITY-CORRECTED AVERAGE AND PEAK TORQUE VALUES (IN NEWTON-METERS) FOR THE NEUROMUSCULAR ELECTRICAL-STIMULATION AND VOLITIONAL EXERCISE GROUPS*

		Quadriceps		Hamstrings	
Velocity	Torque	Involved	Uninvolved	Involved	Uninvolved
90 degrees/sec.					
Electrical stimulation	Average	65.8 ± 10.8	109.4 ± 19.1	41.0 ± 5.6	60.6 ± 7.6
	Peak	114.8 ± 21.0	173.0 ± 30.9	75.2 ± 11.1	94.8 ± 13.9
Volitional exercise	Average	36.8 ± 6.5	96.6 ± 11.2	38.2 ± 11.0	57.6 ± 7.0
	Peak	63.6 ± 11.3	168.8 ± 23.3	61.0 ± 15.7	82.8 ± 14.0
210 degrees/sec.					
Electrical stimulation	Average	46.8 ± 6.0	76.2 ± 12.9	39.4 ± 5.3	45.0 ± 6.2
	Peak	95.2 ± 14.4	139.4 ± 24.3	68.4 ± 9.3	82.4 ± 12.3
Volitional exercise	Average	26.6 ± 4.5	71.4 ± 11.4	28.8 ± 7.8	39.0 ± 3.4
	Peak	56.4 ± 11.4	130.8 ± 20.3	53.4 ± 14.0	79.2 ± 8.1

* Values are given as means and standard errors.

instructed to remove the postoperative orthotic device and to watch and palpate the quadriceps during the contraction. The volitional exercise group was also seen three times each week to evaluate the performance of the exercise regimen. All patients kept an exercise log to check compliance with the exercise program. In addition to the experimental protocol, all patients received the following treatment: passive range-of-motion exercises with use of the isokinetic dynamometer, thirty repetitions per treatment at 10 degrees per second; isokinetic exercises for the hamstrings at progressively increasing speeds of contraction, beginning in the second postoperative week; and isokinetic cycling at ninety revolutions per minute for ten minutes per treatment, beginning in the fifth postoperative week. This was a standard regimen for rehabilitation after reconstruction of the anterior cruciate ligament for patients in our clinic and others at the time when the study was undertaken[6,40,62].

Analysis

Gait Analysis

Instrumentation: The gait analysis was performed in the Motion Analysis Laboratory of the NeuroMuscular Research Center at Boston University in the eighth postoperative week. Small, rigid segments were attached to the shank and the thigh. The segments were instrumented by infrared light-emitting diodes, monitored by the Watsmart optoelectric camera system (Northern Digital, Waterloo, Ontario, Canada). Two cameras were calibrated with the use of a standard calibration frame placed in three different locations along the walkway. The calibration procedure uses the 1.43-cubic-meter-calibration frame instrumented with infrared light-emitting diodes that are separated by known, fixed distances as a reference for the distances measured during the gait analysis. The cameras were located two meters apart and provided a field of view of one full stride (heel-strike to ipsilateral heel-strike). Errors in calibration were all less than three millimeters. The variables of interest were observed at a sampling frequency of 100 hertz and were recorded on an IBM AT microcomputer. An instrumented foot-switch system was used to identify specific events in the gait cycle. The output from the foot-switches was connected to a twelve-bit analog-to-digital converter (Watscope, Northern Digital) and was sampled at a frequency of 300 hertz. Kinematic data were transferred to a VAX 11/750 (Digital, Maynard, Massachusetts) and were processed with the TRACK rigid-body-analysis software (Human Rehabilitation and Biomechanics Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts). This program calculates the six degrees of freedom of a rigid segment, such as the shank or the thigh, in an inertial reference system and uses that information to calculate the kinematics of the joint. Additional analysis was performed with the ANAGAIT anatomical reference-frame software (Motion Analysis Laboratory, NeuroMuscular Research Center). This program uses the calculations of the angles made by TRACK and calculates angles in a joint coordinate system, resulting in the calculation of actual anatomical angles. For the knee, this system is based on the work of Grood and Suntay[21]. The foot-switch data were analyzed with software developed by the NeuroMuscular Research Center.

Procedure: Four pentagonal arrays of five infrared light-emitting diodes were attached to points on the thigh and leg bilaterally. Segments were attached so that the Z-axes of the arrays were aligned with the shaft of the femur or tibia. Foot-switches were affixed bilaterally to the plantar surface of the heel, the mid-part of the sole, and the great toe. The patient then stood in the center of the walkway, and a three-second static trial was recorded. The patient subsequently walked five times along a ten-meter walkway, and five three-second walking trials were recorded. The criterion for trials selected for analysis was the presence of a complete data set. Data were then processed with the TRACK and ANAGAIT software to determine angles of flexion of the knee during stance. The stride period was determined from the foot-switch data and was verified by examination of displacement of the Y-axis of the left-shank segment with respect to the ground (the walkway) during the gait cycle. The stride length was similarly determined, and the velocity of walking was calculated from these data. The stance time and cadence were determined from the foot-switch data.

TABLE II

ARTHROMETRIC MEASUREMENTS OF ANTERIOR TIBIOFEMORAL DISPLACEMENT (IN MILLIMETERS)*

Case	Preop.	Intraop.	6 Mos. Postop.	1 Yr. Postop.†	Normal Knees
1	8/10	2/3	2/3	3/5	4/6
2	12/14	3/4	3/5	5/6	5/6
3	11/15	2/4	3/5	NA	3/5
4	13/15	2/4	2/4	3/4	3/5
5	14/16	2/3	3/5	4/6	4/6
6	12/15	2/3	6/8	6/8	5/7
7	10/13	2/3	4/6	5/7	4/6
8	14/20	3/4	4/6	4/6	4/6
9	12/15	2/3	3/4	3/4	3/5
10	14/16	2/4	3/4	3/4	3/4

* Measurements were obtained with a twenty-pound (eighty-nine-newton) anterior drawer test and at the examiner's maximum manual force, with the knee in 30 degrees of flexion.

† NA = not available.

Measurement of Muscle Performance

Instrumentation: Isokinetic muscle performance at 90 and 210 degrees per second was assessed one day after the gait analysis. For the purposes of this study, strength was defined as the maximum force or torque that a muscle group can generate at a specified velocity[32]. Muscle performance was tested in the Department of Physical Therapy, Sargent College, Boston University. Measurements of muscle performance were recorded with an isokinetic dynamometer (KINCOM; Chattanooga Corporation, Chattanooga, Tennessee). The dynamometer was calibrated before the testing of each patient. Average and peak torque were calculated with the KINCOM software.

Procedure: The patient was placed in the sitting position, and the axis of rotation of the dynamometer was aligned with that of the knee. The lever arm of the dynamometer was secured with a Velcro strap just proximal to the level of the malleoli. Stabilization was provided by additional Velcro straps at the thigh, pelvis, and thorax. The patient was allowed a short period of familiarization at each test speed. The analysis of muscle performance consisted of isokinetic measurements of peak and average torque in a range of motion from 45 to 90 degrees of flexion of the knee, measured at 90 and 210 degrees per second. The order of the muscle-performance tests was randomized. Isokinetic muscle performance was measured with three trials at each velocity. Maximum voluntary peak and average torque were defined as the maximum values of the three trials.

Analysis of Joint Laxity

Joint laxity was measured preoperatively, intraoperatively after reconstruction, and at three, six, and twelve months postoperatively. Measurements were made by one of us (A. A. S.) using a KT-1000 arthrometer (MedMetric, San Diego, California). Anterior drawer testing was performed with the knee flexed 30 degrees. The anterior displacement of the tibia on the femur was measured in millimeters at twenty pounds (eighty-nine newtons) and at the examiner's maximum manual force.

Data Management and Analysis

The range of raw measurements of torque varied widely among the patients, making meaningful comparison difficult (Table I). Therefore, average and peak torque values for the involved knee were normalized to the corresponding values for the contralateral, uninvolved extremity, so that the data could be presented in a manner facilitating comparison among patients.

The statistical analysis was based on a post-test design[9]. Two groups were defined: neuromuscular electrical stimulation and volitional exercise. The statistical study included an analysis of variance to determine the differences in measured variables for gait between involved limbs by group (group effect). Similarly, an analysis of variance was used to analyze the variables of muscle performance normalized to the contralateral extremity. An analysis of covariance was used to compare raw data on torque for the involved limbs by group, with torque values for the contralateral limb as covariates. Significance was accepted for $p < 0.05$. The kinematic data were also analyzed descriptively, and measured variables for stance were correlated with strength of the quadriceps femoris with use of a Pearson product moment. The reliability of the torque and kinematic data (defined as trial-to-trial variability of the measurements) was determined with an intraclass correlation coefficient (formula 2,1).

Results

The exercise logs showed that all patients complied with the home exercise program. All patients completed the treatment programs. There were no missed treatments in either group. For technical reasons, usable kinematic data were obtained for only six patients; this occurred because of a problem with the linearity of the camera. All of these patients had had grafts of the tendon of the semitendinosus muscle and ligament augmentation. The temporal (footswitch) data on which the statistical analysis of stance time, cadence, and velocity was based were unaffected by the problem with the camera and were obtained for all ten patients. Data on flexion and extension of the knee showed trial-to-trial variability averaging 2 degrees, similar to that reported by others[27,53]. The reliability of the torque measurements was 0.98, as determined by the intraclass correlation coefficient.

Joint Laxity

The arthrometric measurements are summarized in Table II. There was no evidence of tibiofemoral laxity (as measured by comparison of the laxity of the involved knee with that of the uninvolved knee) in any patient for as much as twelve months after the operation. The correlation between joint laxity and extension of the knee in stance phase was -0.37 and was not significant.

TABLE III

AVERAGE AND PEAK TORQUES FOR THE VOLITIONAL EXERCISE AND NEUROMUSCULAR ELECTRICAL-STIMULATION GROUPS*

Velocity	Torque	Quadriceps (Per cent)	Hamstrings (Per cent)
90 degrees/sec.			
Volitional exercise	Average	46.7 ± 3.1	74.0 ± 10.4
	Peak	43.5 ± 3.7	71.2 ± 7.8
Electrical stimulation	Average	70.1† ± 6.0	68.6 ± 2.3
	Peak	68.7† ± 5.4	78.9 ± 3.3
210 degrees/sec.			
Volitional exercise	Average	43.7 ± 2.8	75.8 ± 8.0
	Peak	46.4 ± 2.8	72.8 ± 11.2
Electrical stimulation	Average	68.9‡ ± 4.8	87.0 ± 8.3
	Peak	71.0‡ ± 4.3	84.1 ± 4.8

* Values for the involved limbs were normalized to those of the uninvolved limbs. Values are given as means and standard errors.

† Significantly different from the volitional exercise group ($p < 0.05$).

‡ Significantly different from the volitional exercise group ($p < 0.01$).

Analysis of Muscle Performance

The values for average isokinetic torque and peak torque of the quadriceps femoris at both 90 and 210 degrees per second were significantly greater in the neuromuscular electrical-stimulation group than in the volitional exercise group ($p < 0.05$) (Table III and Fig. 2). At the test velocity of 90 degrees per second, the peak torque of the quadriceps femoris, normalized to that of the uninvolved extremity, was 69 per cent in the neuromuscular electrical-stimulation group and 44 per cent in the volitional exercise group; normalized values for average torque were 70 per cent in the neuromuscular electrical-stimulation group and 47 per cent in the volitional exercise group. At the test velocity of 210 degrees per second, the peak torque of the quadriceps femoris, normalized to that of the uninvolved extremity, was 71 per cent in the neuromuscular electrical-stimulation group and 46 per cent in the volitional exercise group; normalized values for average torque were 69 per cent in the neuromuscular electrical-stimulation group and 44 per cent in the volitional exercise group. There were no significant differences between the two groups in any measures of performance of the hamstring muscles (Table III).

Gait Analysis

Temporal Analysis

Foot-switch data from all ten patients were analyzed. With regard to normalized stance time, there was a significant difference ($p < 0.05$) between the two groups (neuromuscular electrical-stimulation group, 50 per cent, and volitional exercise group, 43 per cent). The average cadence of the neuromuscular electrical-stimulation group was significantly faster than that of the volitional exercise group (57.5 compared with 51.4 strides per minute) ($p < 0.05$). Walking velocity was also significantly slower in the volitional exercise group than in the neuromuscular electrical-stimulation group (1.15 compared with 1.43 meters per second) ($p < 0.05$) (Table IV).

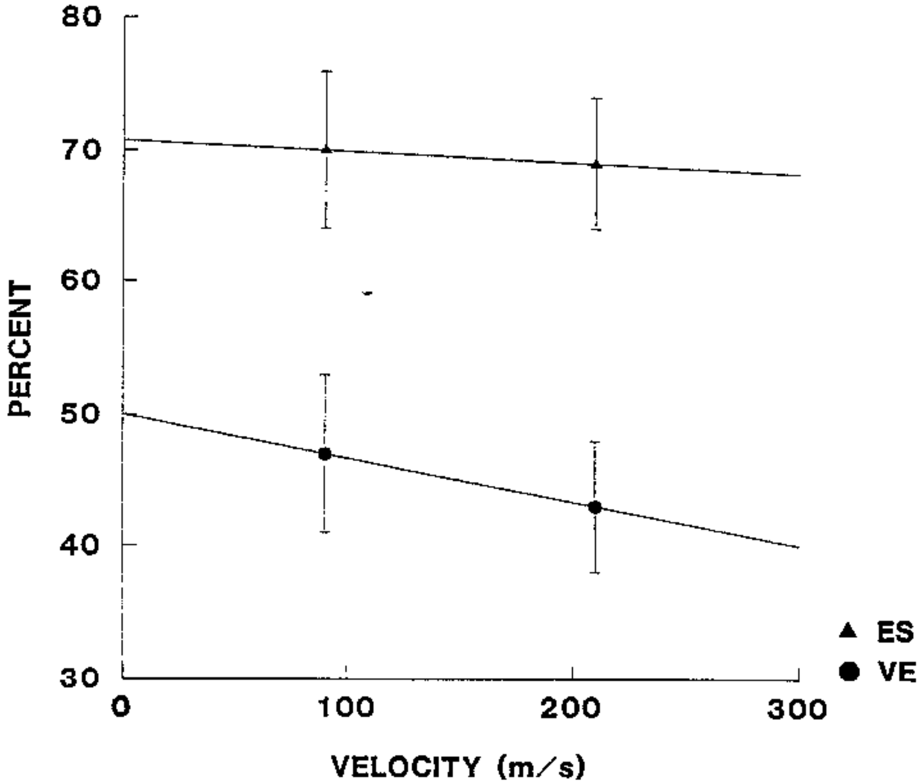

FIG. 2

Graph showing isokinetic torque of the quadriceps femoris as a function of contraction velocity. ES = electrical stimulation and VE = volitional exercise.

Kinematic Analysis

Normal kinematics for flexion and extension of the uninvolved knees can be seen in the tracings in Figures 3, *A* and *B* and 4, *A* and *B*. As the heel leaves the floor, the knee begins to flex in terminal stance (pre-swing). Flexion increases as the foot comes off the ground (RT in Fig. 4, *B*), to a maximum of approximately 80 degrees after toe-off as the swing limb advances. Midway through the swing phase, the knee extends again, and it reaches full extension at heel-strike (RT in Fig. 4, *B*). The knee begins to flex to a maximum of 15 to 25 degrees and returns to full extension after mid-stance.

TABLE IV

TEMPORAL VARIABLES FOR GAIT*

Group	Stance Time of Involved Limb *(Per cent of Gait Cycle)*	Cadence *(Strides/Min.)*	Walking Velocity *(M/Sec.)*
Volitional exercise	42.7 ± 2.4	51.4 ± 2.2	1.15 ± 0.02
Electrical stimulation	49.5† ± 0.3	57.5† ± 1.0	1.43† ± 0.07

* Values are given as means and standard deviations.

† Significantly different from the volitional exercise group ($p < 0.05$).

The flexion-extension trajectory of the involved knees was qualitatively and quantitatively different from that of the uninvolved knees. The major difference was in the nature of the flexion during stance phase. Rather than having the characteristic flexion-extension motion, the knee remained flexed throughout the stance phase. The involved knee continued to flex as the limb proceeded from the stance phase to the swing phase (Fig. 3, *A*). The trajectory shows an almost total elimination of pre-swing extension in the involved knee (Fig. 3, *A*). The trajectory of the uninvolved knee shows the characteristic flexion-extension sequence during the stance phase (Fig. 3, *B*). The sharp onset of flexion that occurs during pre-swing is delayed until after heel-strike of the contralateral limb (double asterisk, Figs. 3, *A* and *B* and 4, *A* and *B*), while the reverse is true for the uninvolved knee. Some patients had constant flexion of the knee through most of the stance phase (Fig. 3, *A*), while others had it only briefly (single asterisk, Fig. 4, *A*). None of the patients had the normal flexion-extension trajectory for the involved knee, while all of them had the normal trajectory for the uninvolved knee. There was significantly less flexion-excursion in the volitional exercise group than in the neuromuscular electrical-stimulation group ($p < 0.05$).

Performance measures for the quadriceps femoris and flexion-excursion of the knee during stance were highly correlated at both 90 degrees per second ($r = 0.93$, $p < 0.01$) and 210 degrees per second ($r = 0.89$, $p = 0.02$). Chi-square statistics for this correlation matrix were significant at $p = 0.013$, and Bonferroni-adjusted probabilities were also significant at $p < 0.05$.

Discussion

Strength Analysis

Persistent weakness of the quadriceps femoris has been a consistent finding in retrospective studies of outcome after reconstruction of the anterior cruciate ligament. Recovery of strength of the quadriceps after reconstruction of the anterior cruciate ligament has been reported to increase from approximately 40 per cent in the first six months after the operation to almost 80 per cent at twenty-four months (Fig. 5).

The decrease in performance of the quadriceps femoris that was found in our patients after reconstruction of the anterior cruciate ligament was significantly attenuated by the addition of neuromuscular electrical stimulation to the treatment regimen. The torque generated by the quadriceps femoris in the neuromuscular electrical-stimulation group

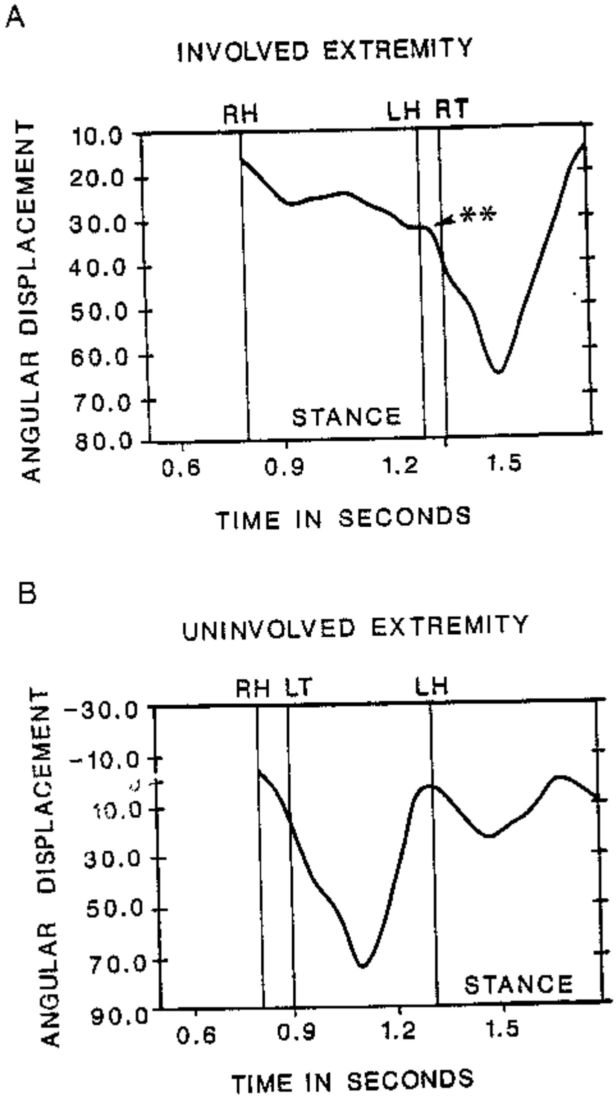

FIG. 3

Graphs showing flexion-extension and flexion trajectories of the involved (*A*) and uninvolved (*B*) knees of a patient in the volitional exercise group. RH = right heel-strike, LH = left heel-strike, RT = right toe-off, and LT = left toe-off.

was approximately 70 per cent of that of the contralateral limb, by all measures. Studies of patients in the early postoperative phase have shown normalized isometric strength of the quadriceps femoris, ranging from 30 to 50 per cent, which is analogous to that of the volitional exercise group in this study[11,67] (Fig. 5). In retrospective studies of patients as many as eight years after the operation, regardless of the rehabilitative regimen, normalized isometric torque has averaged only about 85 per cent of that of the contralateral limb[2,36,64]. In intra-articular repairs, which may be more representative of the patients in this study, isokinetic torque has been even more attenuated — 50 to 60 per cent of that of the uninvolved quadriceps femoris[55]. Conversely, in the only other study we are aware of in which a regimen of neuromuscular electrical stimulation similar to ours was used, Delitto et al. reported normalized values for isometric performance of the quadriceps femoris of 78.8 per cent in the neuromuscular electrical-stimulation group and 51.7 per cent in the volitional exercise group eight weeks after the operation[11]. Their patients trained isometrically, as did those in our study. The patients in the neuromuscular electrical-stimulation group in the present study had strength of the quadriceps femoris in a range usually seen months to years postoperatively (Fig. 5).

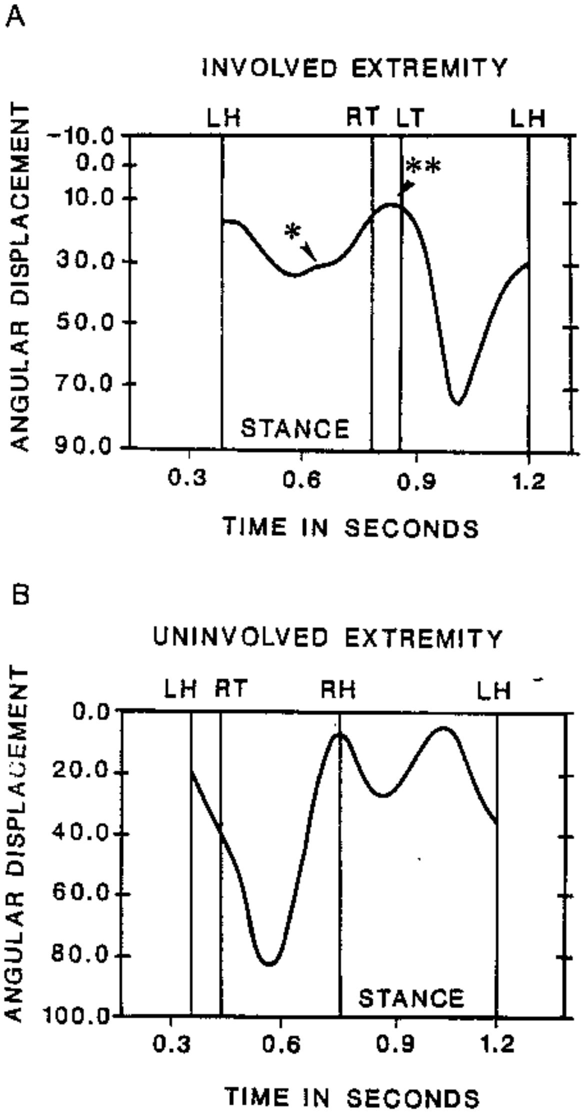

FIG. 4

Graphs showing flexion-extension and flexion trajectories of the involved (*A*) and uninvolved (*B*) knees of a patient in the neuromuscular electrical-stimulation group. RH = right heel-strike, LH = left heel-strike, RT = right toe-off, and LT = left toe-off.

This finding is further underscored when studies concerning knees that have a ruptured anterior cruciate ligament are considered[16,17,54]. The literature suggests that weakness and atrophy of the quadriceps femoris persist in patients who have a ruptured anterior cruciate ligament. In all studies, there has been diminished performance of the quadriceps femoris. Measurements of the quadriceps femoris by cross-sectional area with computerized tomography have been either decreased or unchanged in the area of the knee[17,37,67]. Histochemical analysis of specimens from muscle biopsy has given equivocal results; investigators have found selective type-II atrophy[36], selective type-I atrophy[22], more generalized atrophy[16], and no consistent morphological alterations[17,37]. However, only the vastus lateralis was sampled in most of these studies, and the sampling techniques were rarely adequate to justify the authors' conclusions[7,35]. In most studies of impaired function of the quadriceps after injury to the anterior cruciate ligament, none of these measures correlated well with any other. The relevance of this literature to patients in whom the ligament has been reconstructed is clear when it is realized that the anterior cruciate ligament is also absent in these patients and has been replaced by aneural, avascular graft material. Conversely, the intact anterior cruciate ligament has been shown to be rich in Golgi and Ruffini receptors[10,54].

A series of experiments by Elmqvist et al. and Lorentzon et al. emphasized the seeming paradox of the lack of correlation between cross-sectional areas of the quadriceps femoris, morphological measures, and muscle performance[17,37]. Their work, in combination with that of Baratta et al. and Solomonow et al., suggested that activation of the morphologically normal motor units is altered by disruption of the sensory feedback caused by a tear of the ligament[3,59,60]. They also suggested that the major cause of diminished performance of the quadriceps femoris is altered utilization of motor units.

If activation is reduced, it is reasonable to assume that motor units with higher excitation thresholds may be more affected than more easily excited motor units. In this case, muscles more rich in type-II fibers would be affected by sporadic, discordant activation of these fibers. Elmqvist et al. provided empirical evidence for this theory by demonstrating that the greatest decrease in electromyographic activity in the quadriceps in patients who have a ruptured anterior cruciate ligament occurs in the rectus femoris, the part of the quadriceps with the greatest percentage of type-II fibers[17].

Unlike the quadriceps femoris, the hamstring muscles do not typically display severe or persistent atrophy in this population of patients[64-66]. Persistent atrophy of the ham-

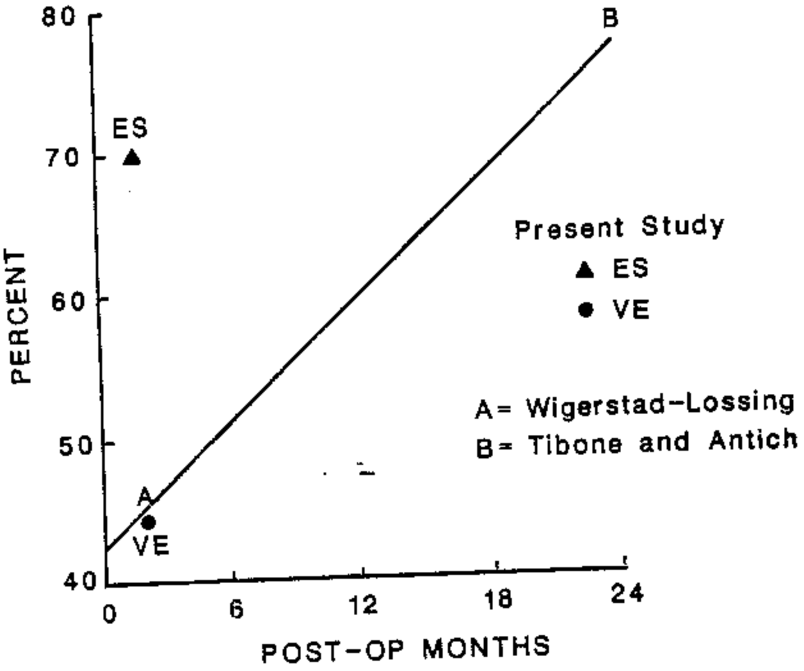

FIG. 5

Graph showing normalized values for torque of the quadriceps femoris in the volitional exercise (VE) and neuromuscular electrical-stimulation (ES) groups in this study compared with those from other studies in which volitional exercise was used for rehabilitation of the quadriceps.

strings has not been observed in the long-term follow-up studies of patients who have had reconstruction of the anterior cruciate ligament[2,55,64,65]. Although slight deficits in strength have been documented in the early postoperative phase in these patients, full strength usually returns within the first six months[64,65]. The present study supports the finding that the hamstrings are minimally affected by the immobilization and trauma that are associated with this operation.

There was no significant difference in performance of the hamstring muscles between groups, and the torque produced by the involved hamstrings averaged 80 per cent of that of the uninvolved extremity, which is consistent with the findings in other studies of the early postoperative phase after reconstruction of the anterior cruciate ligament. This may be attributed to the fact that patients in both groups were allowed to exercise the hamstrings throughout the available range of motion, beginning in the second postoperative week. All of our patients participated in a regular postoperative protocol, which included isokinetic exercises for the hamstrings at various velocities of contraction (excluding the two test velocities). Contraction of the hamstrings decreases the strain on the anterior cruciate ligament or the graft, and it is encouraged during all phases of rehabilitation.

Marked weakness and atrophy of the hamstrings may not occur for two other reasons. First, three of the four hamstring muscles are biarthrodial, crossing the hip and knee joints. Therefore, even when the knee is immobilized, the hamstrings are active in controlling the position and motion of the hip joint. Basmajian reported that major activity in biarthrodial muscles can be maintained when motion at one of the joints is eliminated[4]. Second, neurophysiological responses of the joint to stress may actually result in facilitation of the hamstrings. Solomonow et al. identified a primary fast reflex arc between the anterior cruciate ligament and the hamstring muscles and a secondary reflex arc from the mechanoreceptors of the capsule and the muscle that activate the hamstrings and inhibit the quadriceps[60]. Both reflexes are activated by strain on the joint. In knees that have a rupture of the anterior cruciate ligament (including those that have had reconstruction), presumably this primary reflex arc is lost. The secondary reflex arc then would result in inhibition of the quadriceps femoris when strains are placed on the joint capsule. As the hamstrings are presumably facilitated by this reflex arc, the lack of atrophy of the hamstrings reported in almost all long-term studies of patients who have had a tear of the anterior cruciate ligament also supports this interpretation. This is true even when the lower extremity has been immobilized, and it may explain the discrepancy between the natural course of the response of the two groups of thigh muscles after operations on the knee.

The effect of neuromuscular electrical stimulation on the quadriceps femoris in our patients may have been due to neurophysiological differences between electrically elicited and voluntary contractions. Electrically elicited contractions are physiologically different from volitional contractions in their frequencies of activation, patterns of depolarization, and perhaps even in the order in which motor units are recruited. The predominant mechanism by which generation of force is increased in large muscles is recruitment. Recruitment of motor units continues to at least 80 per cent of maximum volitional contraction in these muscles[12,14,29,33,41]. Peak firing rates fluctuate at around twenty-five pulses per second for all types of motor units, and rate coding is not a major means of increasing production of force in large muscles[12,14]. Type-II muscle fibers have been shown to be capable of firing at sixty pulses per second under certain conditions, although they do not regularly fire at frequencies of more than twenty-five pulses per second. The relatively low firing rate in type-II fibers that is seen during high-intensity contractions of the muscle (usually about twenty-five pulses per second and reportedly[12] as low as seven to twelve pulses per second) suggests that the fibers may not be fully fused (tetanized), even at high intensities of contraction[12,29] and that there is a potential for the muscle to generate larger levels of force[13].

Electrical stimulation can be used to activate muscle fibers at frequencies of stimulation far greater than both the critical fusion frequency (the minimum firing rate that produces a tetanic response) and the normal firing rate for these fibers. Higher production of force is possible with use of neuromuscular electrical stimulation as compared with volitional contraction, given the higher firing rates that occur in electrically elicited contractions[13]. There is direct and indirect evidence that neuromuscular electrical stimulation activates large-diameter nerve fibers (innervating type-II motor units) before it activates small-diameter nerve fibers[8,15,19,25,56,59,63]. This pattern of recruitment varies to some degree with the geometry of the tissues and is by no means unequivocal[31]. However, electrical activation is often the opposite of that described by the size principle of Henneman et al. and Lüscher et al., which states that the order of recruitment within a pool of motor neurons progresses from the smallest to the largest motor neuron[23,38].

The use of neuromuscular electrical stimulation to activate muscle could short-circuit the effects of reflex inhibition of the quadriceps. External activation of the motor units most easily activated by electrical stimulation may have an effect on subsequent voluntary utilization of these same motor units. Volitional muscle-strengthening may be unable to overcome the effects of this reflex inhibition during volitional exercise, regardless of the level of the rehabilitative training. Lorentzon et al. questioned whether there is any clear "scientific rationale for pure strength training" (such as traditional volitional exercise programs) in these patients[37]. Neuromuscular electrical stimulation may then prevent what some investigators have termed "learned disuse"[65].

Electrically elicited muscle contraction may be better able to augment muscle strength in patients who have weakness. If type-II motor units are activated more easily and at higher firing rates with neuromuscular electrical stimulation than with volitional activation, then neuromuscular electrical stimulation may be more effective than voluntary exercise for the training of type-II motor units. Even at low levels of contraction, more large fast-twitch motor units will be activated with an electrically elicited muscle contraction than with a voluntary contraction. Type-II motor units are not activated in large muscles such as the quadriceps except at high levels of voluntary contraction. Therefore, neuromuscular electrical stimulation in conjunction with voluntary exercise may be a useful treatment for patients who are weak.

Functional Measures

The temporal variables of gait that were measured in this study (cadence, stance time, and walking velocity) demonstrated an improvement in function accompanying the increased strength of the quadriceps femoris in the neuromuscular electrical-stimulation group. Although both the volitional exercise and the neuromuscular electrical-stimulation group had cadences that were slightly slower than normal values for their age and sex, the neuromuscular electrical-stimulation group approached normal cadences of fifty-eight strides per minute in women and sixty-one strides per minute in men[30,43,44]. Stance times of the involved limb were normal in the neuromuscular electrical-stimulation group, with very little variability between patients, but they were significantly decreased in the volitional exercise group. Correlations between cadence and stance time and strength of the quadriceps femoris accounted for only 25 per cent of the differences in these variables ($r = 0.5$). Factors other than strength of the quadriceps — most notably, pain and confidence of the patient — also have an effect on stance time and cadence, but were beyond the scope of this study.

The results of the kinematic analysis indicate that there is a significant effect of strength of the quadriceps femoris on flexion-excursion of the knee during stance. The values for flexion-excursion of the knee during stance were similar to reported age-matched normal values for this population (22.3 degrees) in the uninvolved extremities in both groups (Figs. 3, *B* and 4, *B*). The values for flexion-excursion of the involved extremity in the volitional exercise group were significantly less than normal, while the values for the neuromuscular electrical-stimulation group approached normal[30,43,44,52] (Figs. 3, *A* and 4, *B*).

None of the patients had full extension of the knee of the involved extremity at any time in the gait cycle, although all but one were capable of full passive and active extension of the knee. (One knee lacked less than 5 degrees of extension.) Correlations between laxity and range of motion of the knee joint and maximum extension of the knee during stance were less than 0.3 and not significant. Therefore, it appears that these factors did not affect flexion-extension trajectories of the knee in this group of patients. Although flexed-knee stance is more demanding on the quadriceps femoris[49,69], the moment arm of the quadriceps tendon (measured as the horizontal distance between the point of tibiofemoral contact and the center of the patella) is greatest at 15 degrees of flexion of the knee, increasing the mechanical advantage of the quadriceps femoris at this angle[49]. Perhaps this factor makes slight flexion a point of maximum stability for patients who have a weak quadriceps. The ability of the hamstrings to control motion of the tibia may also be enhanced by having the hamstrings contract closer to the optimum length (a point slightly greater than the resting length of the muscle) throughout stance.

The normal stance phase involves flexion of the knee during the first portion and then full extension that coincides with the transition to the swing phase between heel-off and toe-off (Figs. 3, *A* and 4, *B*). Since returning the knee to full extension before heel-off necessitates a larger force of the quadriceps than maintaining the knee at a fixed angle of flexion, patients who have a weaker quadriceps resort to this solution. This finding is similar to the "quadriceps-avoidance gait" pattern recently reported by Berchuck et al. in patients who had a torn anterior cruciate ligament[5]. The flexion of the knee that occurs during weight acceptance is controlled by eccentrically contracting quadriceps femoris muscles. Although the hamstrings are also contracting at this time, their function may be more of a stabilizing one than one of actively flexing the femur on the tibia. This mechanism may have a latency of a few milliseconds, which is manifested by a rapid flexion of the knee, with the amount of flexion remaining relatively constant throughout the stance phase. Fixing of the knee in slight flexion reflects the decreased support provided by the flexed, involved knee. This finding is corroborated by that of decreased stance times of the involved limb in the weaker patients. The double-support phase during the stance phase of the involved extremity (the time-interval from left to right in Fig. 3, *A*) is shorter than the corresponding interval for the uninvolved limb (the period from right to left in Fig. 3, *B*). This difference in timing is also reflective of the over-all shorter stance time of the involved extremity in these patients. Conversely, in the uninvolved extremities, there are characteristically normal curves of flexion of the knee for the stance phase, rapid flexion of the knee at weight acceptance followed by extension at mid-stance, and flexion again during terminal stance (pre-swing). The trajectories of flexion of the involved knees in the stance phase in our patients were remarkably similar to those of the arthritic patients described by Stauffer et al.[61]. Those authors also reported a reduction in the amount of flexion-excursion of the knee during stance that was correlated with strength of the thigh muscles.

Patients who have stronger quadriceps femoris muscles have less flat curves of flexion (Fig. 4, *A*) than those who have weaker quadriceps femoris muscles (Fig. 3, *A*). This suggests that, for the weaker patients, a quasi-static approximation may be an appropriate model for the stance phase of gait, while the stronger patients deviate from the static model, presumably due to the introduction of dynamic effects.

Although functional outcome has been measured indirectly in patients after reconstruction of the anterior cruciate ligament, with use of functional scales, apparently no previous investigators have directly examined a functional variable such as gait in patients in the early postoperative phase. The results of those other studies have been remarkably similar to the findings of the present study. Arvidsson et al. found a direct correlation between isokinetic peak torque of the quadriceps femoris at 120 degrees per second and functional recovery at five to ten years after reconstruction[2]. Odensten et al. demonstrated a significant correlation between isokinetic performance of the quadriceps femoris at 120 degrees per second and return to the level of mobility before the injury ($r = 0.62$)[47]. Seto et al. showed a direct correlation between strength of the thigh muscles and functional outcome five years after intra-articular reconstruction of the anterior cruciate ligament[55]. The average torques of the quadriceps femoris and hamstring muscles, at 240 and 120 degrees per second, were all highly correlated ($0.74 < r < 0.80$) with functional outcome, as measured by a knee-function scale that was a modification of the scale of Lysholm and Gillquist[39,55].

Over-all, the patients in the neuromuscular electrical-stimulation group in the present study had a more normal gait pattern than did the patients in the volitional exercise group. The quadriceps femoris muscles were stronger, the temporal gait patterns were nearly normal, and the kinematics were more like those of the uninvolved knee. The knees of these patients were stronger in the eighth postoperative week than reported averages for such patients years after the operation[55,64,65]. Our results suggest that the use of neuromuscular electrical stimulation translates, at least in the immediate postoperative period, not only into an increase in muscle strength but also into an improvement in the functional use of the muscles. This may represent a partial compensation for the loss of the anterior cruciate-ligament receptors.

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