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The action of the rectus femoris muscle following distal tendon transfer: does it generate knee flexion moment?

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Rectus femoris transfer surgery involves detaching the rectus femoris from the patella and reattaching it posterior to the knee. While this procedure is thought to convert the rectus femoris from a knee extensor to a knee flexor, the moments generated by this muscle after transfer have never been measured. We used intramuscular electrodes to stimulate the rectus femoris in four subjects, two after transfer to the semitendinosus and two after transfer to the iliotibial band, while measuring the resultant knee moment.

Electromyographic activity was monitored in the quadriceps, hamstrings, and gastrocnemius muscles to verify that the rectus femoris was the only muscle activated by the stimulus. We found that the rectus femoris generated a knee extension moment in all of the subjects tested. This finding suggests that transfer surgery does not convert the rectus femoris to a knee flexor, and that a mechanism exists which may transmit the force generated by the rectus femoris anterior to the knee joint center after distal tendon transfer.

Individuals with spastic cerebral palsy frequently walk with stiff-knee gait, a condition characterized by decreased knee range of motion during swing. Inadequate swing-phase knee flexion hinders toe clearance and often forces these individuals to adopt energetically inefficient compensatory movements to advance the limb. The rectus femoris, which generates hip flexion and knee extension moments, has been targeted as a probable cause of stiff-knee gait (Gage et al. 1987, Perry 1987). During normal walking, this muscle is active for a short period that begins just prior to toe off and ends in early swing phase. During stiff-knee gait, however, the rectus femoris often shows prolonged or continuous activity during swing; this generates a knee extension moment that is thought to inhibit normal knee flexion (Gage et al. 1987, Perry 1987, Sutherland et al. 1990).

Perry (1987) suggested that the rectus femoris could be used to augment swing-phase knee flexion by transferring its distal tendon posterior to the knee. This surgery is now widely used to treat or prevent stiff-knee gait. Two of the most commonly used reattachment sites are the distal tendon of the semitendinosus muscle and the iliotibial band. A number of gait studies have shown that stiff-knee gait frequently improves following rectus femoris transfer: Sutherland et al. (1990) found that swing-phase knee range of motion was improved significantly following isolated rectus femoris transfer. Gage et al. (1987) and Ounpuu et al. (1993a) reported postoperative improvements when rectus femoris transfer was performed with other orthopedic procedures, such as hamstring lengthening. Ounpuu et al. (1993b) also compared postoperative gait kinematics of subjects with rectus femoris transfer and distal tendon release. While both procedures improved knee range of motion (16° and 6° respectively) in subjects who exhibited <80% of normal range of motion (ROM) preoperatively, only the transfer group experienced an increase in peak knee flexion during swing.

While gait studies have shown that rectus femoris transfer may improve swing-phase knee range of motion, the functional differences between transfer sites and the mechanisms behind the improvements are not known. It is thought that transfer converts the rectus femoris from a knee extensor to a knee flexor, thereby allowing it to actively generate a knee flexion moment during swing. However, it is also possible that this surgery simply removes the adverse extension moment generated by the spastic muscle without augmenting knee flexion. Delp et al. (1994) reported data from cadaver experiments and a computer simulation of the rectus femoris transfer which demonstrated that transfer to the semitendinosus gives the rectus femoris a 3 to 5cm knee flexion moment arm, while transfer to the iliotibial band gives the muscle only a small moment arm at the knee (ranging from a 5mm extension moment arm to a 1mm flexion moment arm).

Based on this evidence, we hypothesized that the rectus femoris would generate a knee flexion moment after transfer to the semitendinosus and essentially no flexion–extension moment at the knee after transfer to the iliotibial band. The objective of this work was to test this hypothesis by selectively stimulating the rectus femoris and measuring the moments generated by this muscle after transfer to either the semitendinosus or iliotibial band.

Materials and Methods

The moments generated by the rectus femoris were measured in four subjects who had undergone rectus femoris transfer

(N=2 to semitendinosus, N=2 to iliotibial band) at least one year prior to this study, and in four unimpaired control subjects who had no surgery. The transfer subjects were all males who walked with stiff-knee gait preoperatively and exhibited mild levels of spasticity. All of the subjects underwent additional orthopedic procedures (Table I) at the time of the rectus femoris transfer. Knee range of motion was found to improve by an average of 10° ± 7 (SD) in the three subjects for whom postoperative gait data were available. Testing was performed with informed consent and all experimental protocols were approved by the Institutional Review Board of the Rehabilitation Institute of Chicago.

The experimental set-up was designed to facilitate electrical stimulation of the rectus femoris; measurement of the resulting knee moment; and recording electromyographic (EMG) activity from most of the muscles crossing the knee (Fig. 1). Subjects were seated in an adjustable chair and a 6 degree-of-freedom load cell was placed around the leg just above the ankle. A fiberglass cast provided a rigid interface between the subject and the load cell. The subjects were seated with the knee flexed at 90° and the hip flexed at 40° to 45°. This position was chosen because it was comfortable for the subjects and allowed us to decouple the load-cell forces that contributed to the knee moment from those that contributed to the hip moment. Although 90° of knee flexion is not adopted during gait, seating the subjects in this position provided an accurate method for determining if the rectus femoris could generate a knee-flexion moment.

Bipolar electrodes were inserted into the motor endpoint of the rectus femoris, with an inter-electrode spacing of approximately 1cm, for the purpose of intramuscular stimulation. The motor endpoint was found using a small monopolar surface stimulation electrode which was moved to different points along the muscle path. Proper insertion was verified by having the subject lightly flex his hip while using the electrodes to record the EMG activity.

The rectus femoris was stimulated with a 60ms train of pulses (4 pulses at 50Hz), and the resulting forces and moments were measured at the load cell. The stimulus current was initially set very low and was increased incrementally until the muscle's motor threshold was found. Twelve trials of data were collected using a stimulus intensity slightly above motor threshold. At this stimulus level the rectus femoris was observed to contract and a consistent force response was measured at the load cell. Subjects were allowed to rest for one minute between trials to minimize muscle fatigue. The force signals were digitally sampled at a rate of 4000Hz and were low-pass filtered at 300Hz. The knee moment generated by the rectus femoris was computed for each trial using the forces and moments recorded at the load cell. These data were then averaged for each subject to obtain a mean knee moment. Prior to averaging, all baseline force offsets were removed from the individual trials.

EMG was recorded from most of the muscles that cross the knee to verify that the rectus femoris was the only muscle activated by the stimulus. Surface electrodes were used to record from the rectus femoris, vastus medialis, vastus lateralis, semitendinosus, the long head of the biceps femoris, and the medial and lateral heads of the gastrocnemius. Prior to electrode placement, the skin was lightly abraded to lower skin impedance and provide a better electrode–skin interface.

Intramuscular electrodes were used to record EMG from the vastus intermedius muscle in the control subjects only. Surface electrodes could not be used to record from this muscle because it lies deep to the rectus femoris. Vastus intermedius activity was not monitored in any of the transfer subjects for safety reasons. Individuals with spastic cerebral palsy often exhibit strong reflexive contractions in response to discomfort. If such a contraction were to occur during electrode insertion, the needle could break within the muscle. The vastus intermedius EMG signals recorded from the control group were therefore assumed to be indicative of this muscle's activity in all subjects. All EMG signals were sampled at a rate of 4000Hz and were bandpass filtered at 30 and 2000Hz.

The mean rectified EMG was computed for each muscle during the intervals between stimuli, and a single factor analysis of variance (ANOVA) was used to determine which muscles were activated significantly above baseline levels. Each inter-stimulus interval was broken into two time intervals, a 2 to 3ms period that was contaminated by stimulus artifact and a moving 6ms averaging window over which the mean rectified EMG was computed (Fig. 2). An M-wave is typically seen in the raw EMG trace in response to electrical stimulation (Fig. 2 rectus femoris, left trace). The M-wave represents the period of peak activation and is commonly 5 to 6ms in duration. The 6ms window was therefore used to isolate the M-wave in each inter-stimulus interval for the rectus femoris EMG trace, or the periods of peak activity within the inter-stimulus intervals for muscles that did not generate an M-wave response (Fig. 2 vastus medialis).

Table I: Surgical procedures performed in addition to transfer of rectus femoris to semitendinosus (ST) or iliotibial band (IT), and resulting improvement in knee range of motion during walking

Subject	*Age*	*Additional procedures*	*Δ Range of motion*
IT I	17	medial/lateral hamstring lengthening	+3°
IT II	18	medial/lateral hamstring lengthening	+17°
ST I	17	iliopsoas release, medial/lateral lengthening	+9°
ST II	24	medial hamstring lengthening, femoral derotational osteotomy, calcaneal-navicular fusion, first metatarsal-phalangeal fusion	no data available

For the control group, the EMG recorded during the interstimulus intervals was also expressed as a percentage of the maximum voluntary activation (MVA). Prior to the stimulation protocol, each subject performed maximum voluntary knee flexion and extension tasks under the isometric constraints imposed by the load cell. To compute the MVA, a moving 2ms time window was used to find the maximum rectified EMG for each muscle during the maximum voluntary contractions. The highest value of the mean rectified EMG was assumed to represent 100% activation and the EMG collected during the stimulus protocol was expressed as a percentage of this maximum. Maximum voluntary EMG was not recorded from the transfer subjects because they had difficulty generating maximal contractions and selectively activating specific muscle groups.

Resting EMG was monitored and recorded frequently during the experiment to ensure that the subjects were relaxed and did not anticipate the stimulus. If spasticity or anticipatory activity was noted, testing was interrupted until the subject relaxed and the EMG returned to baseline levels. Prior to data analysis, all of the force and EMG traces were inspected to identify any trials in which the subject showed anticipation of the stimulus. Any trial in which anticipatory activity was seen was excluded from collective analysis. Of the 12 trials of data collected for each subject, typically only 1 or 2 were excluded.

Results

Stimulation of the rectus femoris produced a knee extension moment in all of the control subjects studied (Fig. 3A). Surprisingly, the rectus femoris also generated a knee extension moment after transfer to the semitendinosus (Fig. 3B) and iliotibial band (Fig. 3C). The magnitudes of the knee moments differed between the control and transfer groups. These differences may be attributed to smaller muscle cross-sectional area in the transfer subjects or to an altered moment arm following transfer.

An analysis of variance showed a statistically significant increase ($P<0.0001$) in the averaged rectified EMG of the rectus femoris in every subject tested following stimulation. M-waves were seen following each stimulus pulse in the raw rectus femoris EMG, indicating the synchronous excitation of a large number of motor units. The peak activation of this muscle often exceeded 200% MVA in the control group. Activations of greater than 100% MVA were expected because electrical stimulation causes the synchronous depolarization of a large number of motor units as opposed to the asynchronous motor unit activity seen during voluntary contractions.

Analysis of variance also showed that no muscles other than the rectus femoris were activated above baseline in any of the four transfer subjects ($P>0.05$); however, statistically significant increases from baseline were occasionally seen in three of the four control subjects ($P<0.05$). The largest increases were seen in the vastus intermedius muscle, which

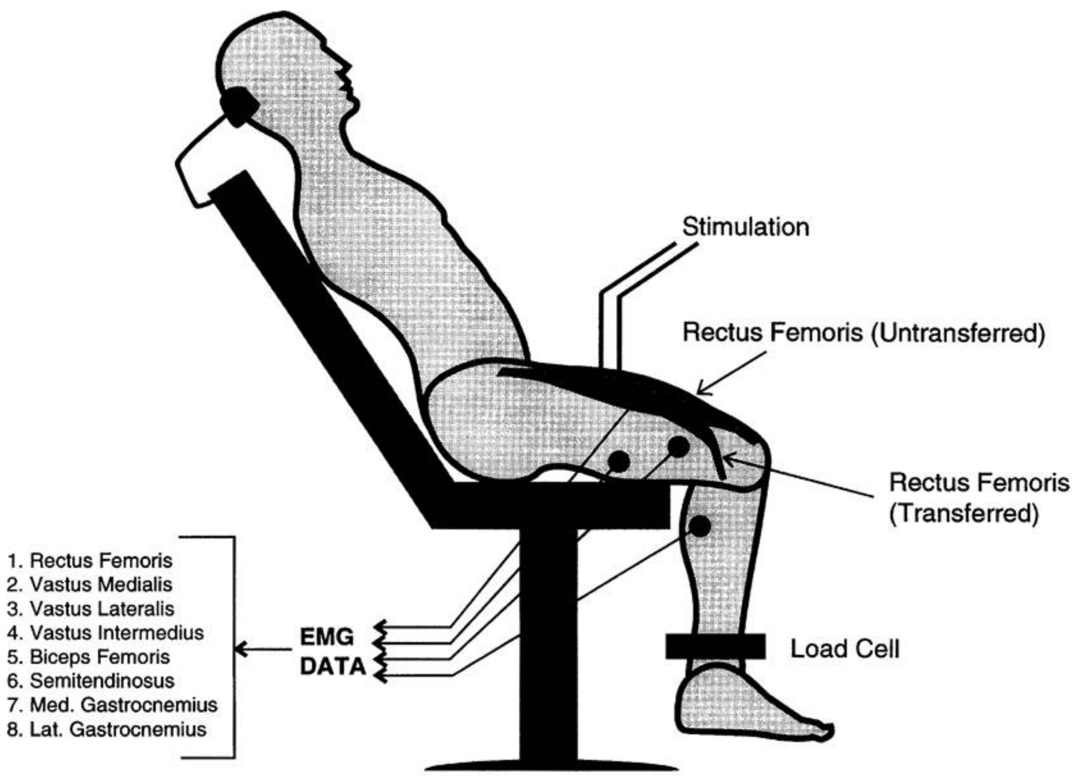

Figure 1: *Experimental set-up. Subject was seated in an adjustable chair with ankle placed through a load cell. Rectus femoris was stimulated intramuscularly while EMG was recorded from eight muscles in the leg. Untransferred rectus femoris is shown as shaded muscle; altered path of transferred muscle is depicted as dark line extending posterior to knee.*

reached a maximum of 2% MVA in one control subject and 6% MVA in a second. These increases were only observed following the third and fourth stimulus pulses, approximately 50ms after the onset of stimulation. While these increases are statistically significant, the force contribution of this muscle was considered negligible for reasons set forth in the 'Discussion'. No other muscles, including the vastus intermedius in the two remaining control subjects, showed increases greater than 1% MVA.

Stimulation of the rectus femoris elicited a spastic reflex response in two of the transfer subjects (Fig. 4). This response was exemplified by the mass activation of many muscles and a large force response. This reflex began approximately 150ms after the first stimulus pulse was delivered. However, within the first 150ms, a force response due only to rectus femoris contraction was obtained. From this data it was possible to compute the knee moment generated by the rectus femoris.

Discussion

The purpose of this study was to determine experimentally if the rectus femoris generates a knee flexion moment after distal-tendon transfer. Delp et al. (1994) have shown, using cadavers and a musculoskeletal model, that the semitendinosus has a large knee flexion moment arm, whereas the iliotibial band has essentially no moment arm at the knee. We therefore expected the rectus femoris to generate a knee flexion moment after transfer to the semitendinosus and only a small moment about the knee after transfer to the iliotibial band. Contrary to our expectation, we found that the rectus femoris generated a knee extension moment following transfer to either location.

It is important to point out that testing only four transfer subjects could have created difficulties in interpreting the data if the measured moments had differed between individuals. However, there was very little subject-to-subject variability in the direction of the generated moment; hence, we are confident that the rectus femoris generated a knee extension moment in the four subjects we studied. While this finding does not rule out the possibility that transfer converts the rectus femoris to a knee flexor in some subjects, it suggests that the muscle continues to act as a knee extensor postoperatively in many instances.

The most important aspect of this study was determining that the rectus femoris was the only muscle activated by the applied stimulus; all of the conclusions are based on the premise that the measured force response was generated solely by the rectus femoris. To verify that the rectus femoris was

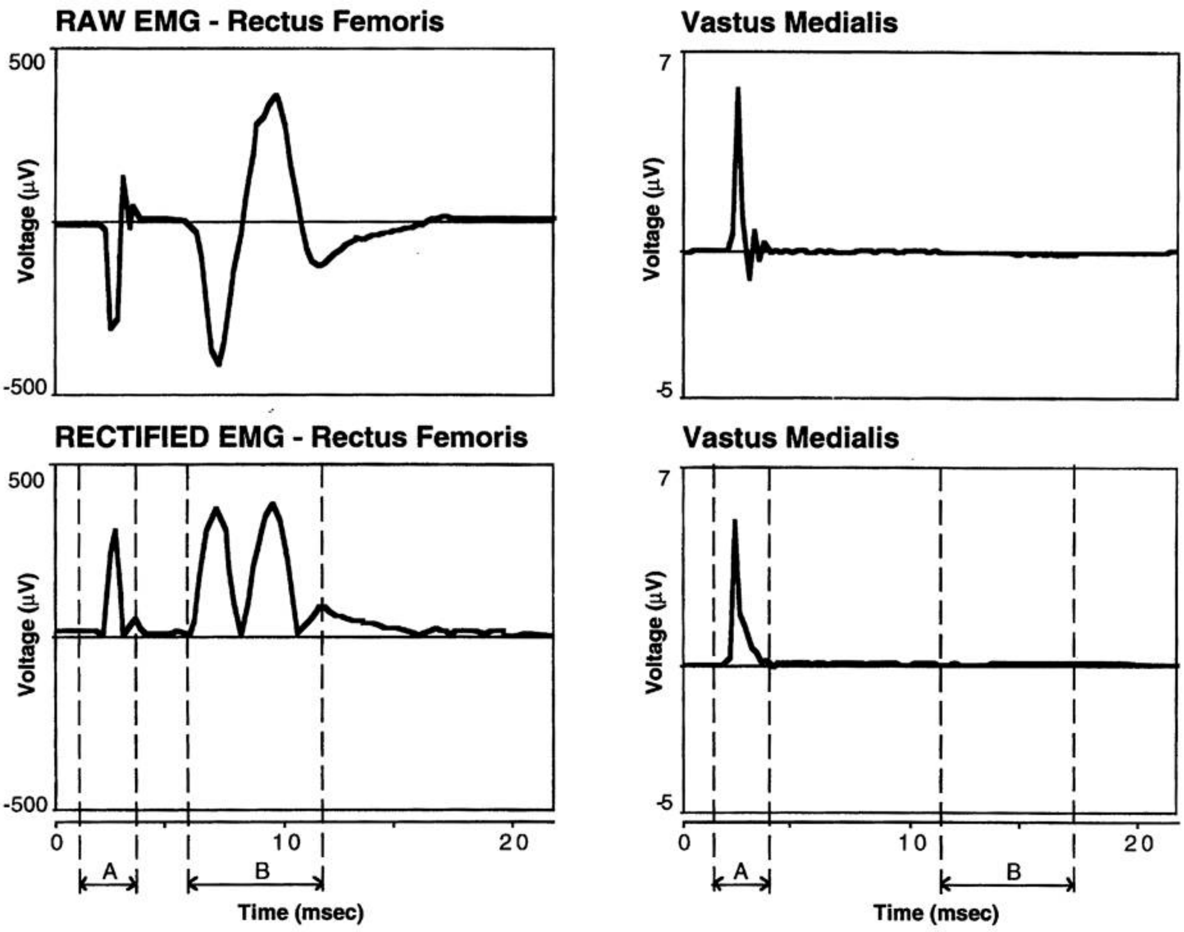

Figure 2: *Analysis of EMG. Raw EMG (shown in top two traces) was first rectified for analysis (lower traces). Each interpulse interval was divided into two periods, A and B. Period A contained stimulus artifact and was discarded from analysis. Period B was a moving 6ms time window over which average rectified EMG was computed.*

the only muscle activated by the intramuscular stimulation, EMG was recorded from most of the major muscles crossing the knee. The rectus femoris was observed to contract strongly in all subjects and showed a consistent increase in its mean rectified EMG in response to the stimulation, often exceeding 200% of the muscle's MVA in the control group. Surface EMG showed that no muscles other than the rectus femoris were activated above baseline in the transfer group, and only the vastus intermedius showed activations greater than 1% maximum voluntary activation in the control group.

The findings from the control group do not rule out the possibility that the vastus intermedius contributed to the measured knee extension moment. However, we believe that such contributions would have been insignificant in comparison with the moment generated by the rectus femoris. The rectus femoris makes up approximately 17% of the total physiological cross-sectional area (PCSA) of the knee extensor group, while the vastus intermedius makes up about 30% of the total PCSA (Friederich and Brand 1990). Thus, if all the quadriceps were activated equally, these two muscles would contribute 17% and 30% of the total knee extension moment, respectively. Although the vastus intermedius is capable of producing approximately twice as much force as the rectus femoris when fully activated, the EMG results show that the

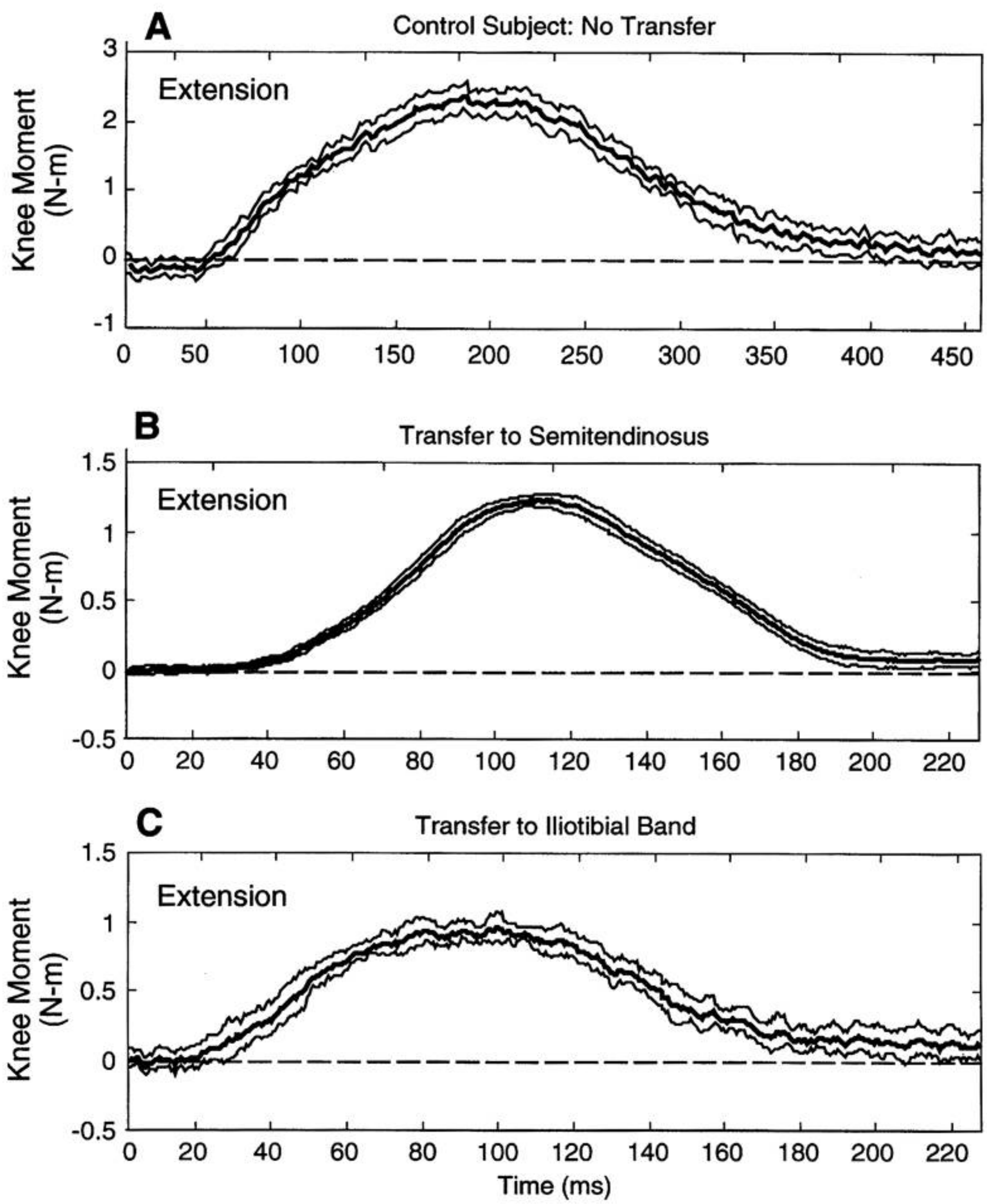

Figure 3: *Knee moment generated by rectus femoris. Rectus femoris generated a knee extension moment in all subjects tested. This figure shows knee moment generated by (A) control subject (B) after transfer to semitendinosus and (C) after transfer to iliotibial band. Each plot represents ensemble average of twelve trials ± one standard deviation. These results are typical of the other subjects from the same test groups.*

percent of maximum voluntary activation for the rectus femoris was typically over 30 times the activation of the vastus intermedius. Rectus femoris activation was over 100 times greater than the activations seen in the remaining quadriceps or hamstring muscles. These large differences in activations led us to conclude that the moments generated by the vastus intermedius and all muscles other than the rectus femoris were insignificant in the control group.

Additionally, we assumed that the conclusions drawn from the control studies, which included the maximum voluntary contractions and recording EMG from the vastus intermedius, were representative of the transfer subjects as well. The experimental protocol was held constant for all subjects, and the EMG results for all muscles other than the vastus intermedius were consistent between the control and transfer groups. We therefore had no reason to believe that the vastus intermedius would be the only muscle to show differences between test groups. Even though we could not record maximum efforts from the transfer group, none of the muscles other than the rectus femoris showed significant increases in activation above baseline during stimulation. This provides evidence that the rectus femoris was activated exclusively in the transfer subjects.

Testing was performed with the knee flexed at 90° and the hip flexed at 40° to 45°. This is not a position that is adopted during walking, when the hip and knee are more extended. This change in body position could affect the magnitude of the moment generated by the rectus femoris by altering its length or moment arm. However, the direction of the knee moment generated by the rectus femoris should not be affected.

Since transfer did not convert the rectus femoris to an active knee flexor in any of the subjects tested, the question remains as to why gait is sometimes improved following transfer. In the four transfer subjects studied here, the rectus femoris generated a knee extension moment when stimulated, yet the three subjects in this study for whom postoperative gait analysis data were available showed an average improvement of 10° ± 7 (SD) in knee range of motion during walking. Each of the subjects in this study underwent additional orthopedic procedures, including hamstring lengthening, at

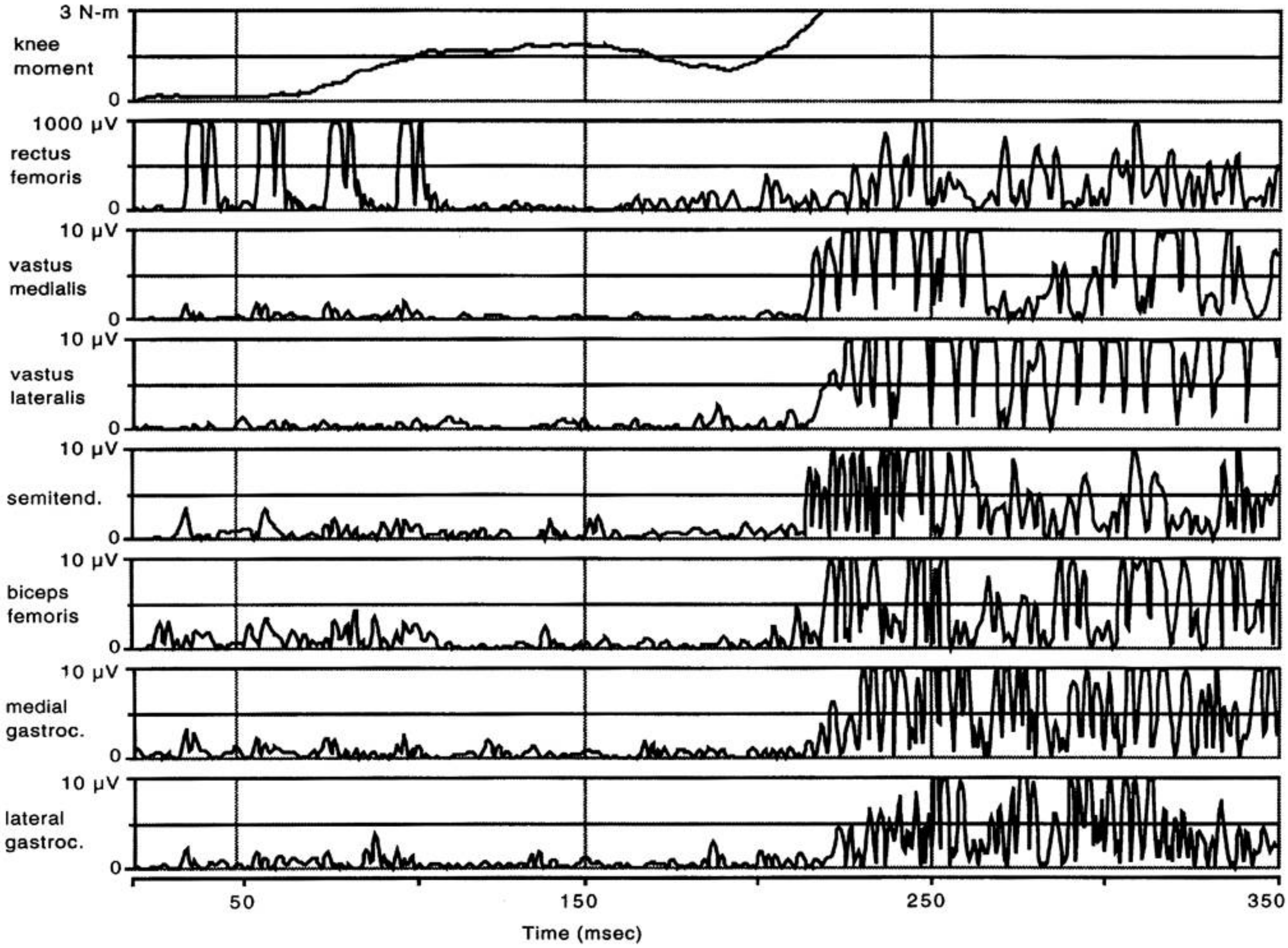

Figure 4: *Spastic reflex response. In two transfer subjects, large increases in EMG and force signals were obtained in response to intramuscular stimulation of rectus femoris. This reflex response occurred approximately 150ms after stimulation onset. In most trials a force response due only to the contracting rectus femoris (top trace) could be detected prior to onset of reflex response.*

the time of the rectus femoris transfer. It is possible that the observed improvements in gait were due to any of these other operations. Studies by Damron et al. (1993) and Thometz et al. (1989) have suggested, however, that hamstring lengthening alone does not improve knee range of motion during walking. Also, Sutherland et al. (1990) have demonstrated that knee range of motion can be significantly improved when rectus femoris transfer is performed alone.

An alternative explanation as to why this surgery improves swing-phase knee range of motion is that transfer places the muscle in a position where it is not passively stretched prior to toe off or during swing. In this case, the stretch reflex would not be excited and the muscle would not generate an adverse knee extension moment during swing. However, if the rectus femoris is reattached too tightly, it may still be stretched prior to toe off and interfere with swing-phase knee flexion. This may provide a possible explanation as to why knee range of motion does not improve in all subjects following transfer.

Rectus femoris transfer may also be effective because this surgery maintains the muscle's function at the hip postoperatively. Perry (1987) suggested that this could be attained through distal transfer or release while still improving knee motion during swing. Subsequent studies by Ounpuu et al. (1993b) have shown that subjects with distal transfer of the rectus femoris had significantly better knee range of motion postoperatively when compared with subjects with distal release. Transfer could place the muscle at a more optimal position on the length-tension curve, better preserving the muscle's hip flexion capability. Perry (1987) and Kerrigan et al. (1991) have suggested that hip flexion moment is important for ensuring adequate knee flexion during swing. Piazza and Delp (1996) have shown that swing phase knee flexion increases with increased hip flexion moment via dynamic coupling between limb segments. Thus, if the rectus femoris transfer maintains hip flexion strength better than distal-tendon release, this may allow for greater knee flexion during swing.

The findings of this study suggest that a mechanism exists that allows the force developed by the rectus femoris to be transmitted anterior to the knee joint center after transfer. It is possible that fascia or scar tissue connecting the rectus femoris to the surrounding knee extensors transmits a portion of the developed force anterior to the knee. Thus, when the rectus femoris contracts, these connections become taut and transmit force to the knee extensors which, in turn, generate a knee extension moment. In transfer surgery, it may be difficult to free the muscle from the surrounding fascia along the proximal half of the muscle. Also, scar tissue formation may increase the connections between the rectus femoris and the knee extensors, and muscle remodeling may occur. These mechanisms may influence the moments generated by the rectus femoris postoperatively.

Our findings suggest that muscle function following transfer may not be intuitively obvious. Connections between muscles may play a more significant role in force transmission postoperatively than was previously thought. By minimizing these connections, it may be possible for the rectus femoris to generate a knee flexion moment following transfer. Even though the rectus femoris was found to generate a knee extension moment after transfer, all of the subjects for whom postoperative gait data was available showed improvements in their gait. This result is puzzling and highlights the need for further work to determine the factors that cause stiff-knee gait and the mechanisms through which swing-phase knee range of motion may be improved following transfer.

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