Hiroshima J. Med. Sci.
Vol. 49, No. 4, 145~151, December, 2000
HIJM 49–23

The Main Factor Causing Prolonged Reaction Time on Force Producing Process Following Anterior Cruciate Ligament Reconstruction

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ABSTRACT

This study investigated the electromechanical properties of atrophied human quadriceps femoris muscle during a voluntarily elicited maximal isometric contraction (MVC) and a peripherally stimulated twitch contraction. Nineteen patients were recruited 2–3 months following a unilateral anterior cruciate ligament (ACL) reconstruction. Both the involved leg as well as the uninvolved leg were studied. Maximal twitch response was elicited and surface electromyograms (EMG) were recorded from the vastus lateralis. Total reaction time (TRT) for both MVC and twitch on involved leg was prolonged (251.47 msec, 26.01 msec). This prolongation suggests an extended lag in avoiding injury such as during sports. Pre-motor time during both MVC and twitch (PMTmvc, PMTtwitch) did not differ between both groups. Electromechanical delay during MVC (EMDmvc) was prolonged on involved leg (53.42 msec), and also evoked twitch EMD (EMDtwitch) (20.04 msec) as compared to the opposit side. Prolonged EMDtwitch may be due to a decrease in stiffness of the series elastic component, changes of peripheral muscle composition to containing more slow type muscle fibers, or a decrease in function of the excitation-contraction (E-C) coupling process. A prolonged EMDtwitch can also explain the prolonged EMDmvc. These findings also suggested that prolonged TRTmvc to visual stimulus during MVC in atrophied human quadriceps femoris muscle after disuse was principally due to prolongation of EMDmvc. Prolonged EMDmvc may have resulted from decreased muscle stiffness, which was evident in the prolongation of the EMDtwitch.

Key words: *Anterior Cruciate Ligament, Electromechanical delay, Disuse, Electromyography*

A reduction in muscle strength is often accompanied by muscle atrophy[2,6,13,20,22,23,26,28,29,31], however this reduction in strength may be relatively greater than the decrease in the muscle mass due to atrophy[13,27,31]. Therefore, the loss of muscle strength is considered to be caused not only by the quantitative decrease in the muscle mass but also by a reduction in the efficiency of the muscle to generate force. Loss of muscle efficiency has been associated with factors that include the neuromuscular function and muscle stiffness[9].

Karpakka et al reported that activities of prolyl 4-hydroxylase and galactosylhydroxylysyl glucosyltransferase which are used for estimating alterations in the rate of collagen biosynthesis under different experimental and clinical conditions, decreased after three weeks of immobilization[15]. The biochemical studies by Karpakka et al[15] and Nakagawa et al[19] indicated that decrease of collagen fiber thickness leads to decrease in the tensile strength of series elastic components following disuse after orthopedic surgery in humans. Widrick and Fitts reported a reduction of muscle fiber stiffness following non-weight-bearing in rats[33]. A decrease in the stiffness of series elastic components may lead to a decrease in the efficiency of propagation of contractile tension to bones. This may result in a reduction in the muscle strength and delayed responses in physical activities. These studies have lead us to a hypothesis that alterations of electromechanical properties following disuse contributes significantly to the clinical findings in these patients.

Several studies have identified a proprioceptive deficit in knee articular structures following ACL reconstruction[4,5,8,16,17,24,25]. Lysholm et al showed significant deficits of postural control and prolonged reaction time in the ACL deficient group[17]. Though prolonged reaction time is commonly understood to be the result of a proprioceptive

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deficit, we reported that electromechanical delay and reaction time were prolonged to visual stimuli in ACL reconstructed patients[14]. Eventually, we have hypothesized that prolonged reaction time to visual stimuli is selectively attributable to a deficit in peripheral muscle stiffness for series elastic components or a prolonged central nervous system processing time, because reaction time to visual stimuli does not include the afferent time from proprioception. There have been few studies in investigating whether changes in electromechanical responses in voluntary muscle contraction of the human quadriceps femoris muscle is influenced by the change of stiffness for peripheral muscle series elastic component and/or central nervous system processing time following disuse and ACL reconstruction.

The purpose of this study was to investigate the electromechanical properties of atrophied muscle in patients with ACL reconstruction, and to examine the relationship of changes in these properties for voluntarily elicited maximal isometric contraction and peripherally stimulated twitch contraction.

METHODS

Subjects

Nineteen patients (9 men, 10women, age; 27.5 ± 7.1) were studied at least two months after ACL reconstruction. Reconstruction of the ACL was carried out under endoscopy (one-incision) with double-looped autogenous semitendinosus-gracilis tendons[18]. Therefore, no surgical insult was applied to the quadriceps femoris muscles. The mean interval between the injury and operation was 7.5 months (2–26 months). Complications of ACL injury observed in our patients were medial and lateral meniscus partial menisectomy in one and medial meniscus partial menisectomy in four. Patients followed a postoperative rehabilitation protocol developed by the Hiroshima Kyoritsu Hospital, to which the subjects were admitted (Table 1). No subject had a knee laxity measure of more than 3 mm between sides, as determined by the KT-2000 arthrometer (MEDmetric Corp.) at 133 newtons of loading at least six months after ACL reconstruction.

Prior to the following measurements, the femoral girth was measured with a tape measure as a parameter of muscle atrophy. This measurement was performed 10 cm and 15 cm above the upper margin of the patella (AP10 and AP15, respectively).

EMG analysis

The EMG signal was recorded from the vastus lateralis (VL) using bipolar surface electrodes (Model blue sensor, Medicotest Inc.) placed over the center of the belly of the muscle. Care was taken to ensure similar placement of electrodes on both sides. Before the electrodes were attached, the skin area was abraded using a skin prepping gel (D. O. Weaver & Co.) and rubbed with alcohol. The inter-electrode distance was approximatively 2.5 cm. Impedance was checked and only values below 5kΩ were accepted. An amplifier (BIO amp ML132, ADInstruments Pty Ltd.) with adjustable gain was used to register the EMG activity. The EMG signal (bandwidth ranging from 10Hz to 500Hz for MVC, and from 10Hz to 5kHz for twitch) was recorded online by an FM tape recorder (Model XR-5000, TEAC). The analog signals were subsequently digitized at 1000 samples per second for MVC and 10k samples for twitch by a Mac Lab analog-to-digital converter. Data were analyzed on a Power Macintosh 7100/66AV with CHART ver. 3.6.2/s (AD Instruments Pty Ltd).

Table 1. Hiroshima Kyoritsu Hospital rehabilitation guidelines for endoscopically ACL reconstruction over 2 months.

to Week 2
- Knee brace motion ~ −30
- Continuous passive motion 2 hours per day; increase range of motion as tolerated.
- Wall slide.
- Wall pushingu at 90°
- Seated hamstrings (carpet drags).
- Leg curl.
- Straight leg raise with extension lag.
- Hip progressive resistance exercise.

Week 2
- Two-crutch ambulation in brace.
- Isometric quadriceps contraction at 90° with double sports cords.
- Sports cord: knee flexion.

Week 3
- Partial weight bearing (1/3 to1/2).
- Isometric sitting.
- Calf raises with isometric sitting.

Week 4
- Full wight bearing with crutches.

Week 6
- Half squatting.
- Stationary bicycle.

Temporal electromechanical properties for voluntary contraction

Maximal isometric force was measured using Cybex Norm isokinetic dynamometer (Henlly Health Care Corp.). Force data was recorded online by an FM tape recorder simultaneously with EMG, and also processed in a similar way to EMG. Subjects were examined while sitting with the knee flexed at 90 degrees. A stimulus light was presented to the subject immediately after voice instruction to be ready for testing. After presentation of the light stimulus, the subject performed a "ballistic" MVC for five seconds. An example of the recorded output is displayed in Fig. 1.

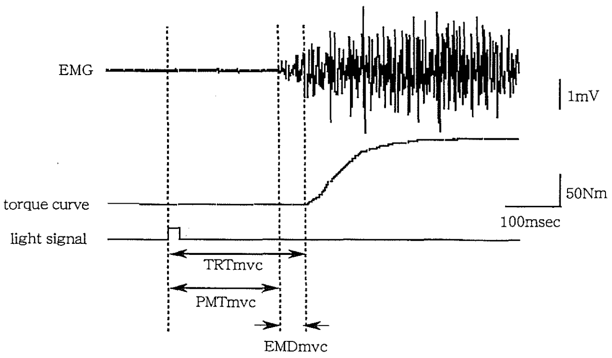

Fig. 1. Sample EMG recording and torque curve during MVC showing how time intervals were determined.
TRTmvc, the total reaction time for MVC; PMTmvc, pre-motor time for MVC; EMDmvc, electromechanical delay for MVC.

Three characteristics were determined:

(1) Total reaction time (TRTmvc), defined as the time interval from the application of the light stimulus to the beginning of force generation.

(2) PMTmvc, defined as the time interval from the onset of the light stimulus to the onset of the myoelectric activity.

(3) EMDmvc, defined as the time difference between TRTmvc and PMTmvc.

As with force, the onset of electromyographic activity was defined as the point where the amplitude becomes 1% greater than the maximal value of the background noise. Background noise was observed during the 3s before the light stimulus. Mean ± SD threshold values for force and EMG were 0.57 ± 0.11 Nm and 24.7 ± 4.8 μV respectively.

Peripheral temporal electromechanical properties

Maximal isometric twitch force, and maximal M-wave detected from VL was recorded in the same way as MVC. Subjects were examined while seated with the knee flexed at 90 degrees. The femoral nerve was stimulated (Model Electronic Stimulator 3F 46 & Isolator 5384, NEC San-Ei) with two felt type electrodes placed parallel to the axis of the nerve at the inguinal region[26]. Isometric twitch contraction was elicited by a supramaximal square wave voltage pulse with a duration of 1ms. The electromechanical properties were quantified according to three temporal characteristics (Fig. 2):

(1) Total reaction time (TRTtwitch), defined as the time interval from the application of the electric stimulus to the point at which the force threshold was exceeded.

(2) PMTtwitch, defined as the time interval from the onset of the electric stimulus to the onset of the M-wave.

(3) EMDtwitch, defined as the time difference between TRTtwitch and PMTtwitch.

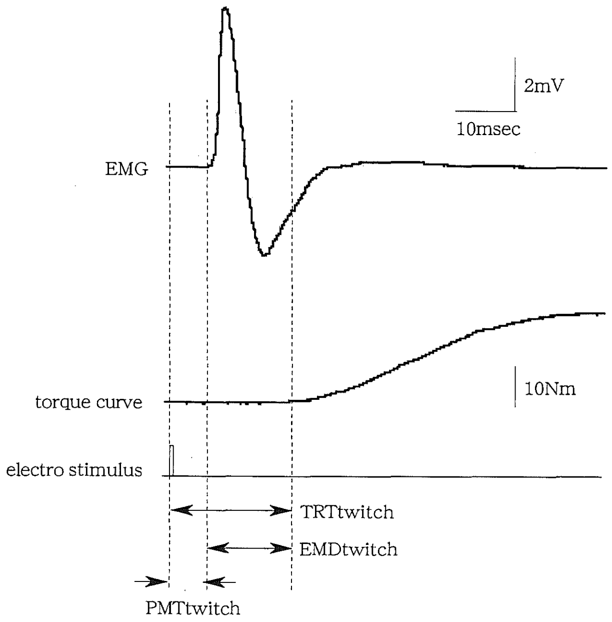

Fig. 2. An example of evoked EMG and torque curve showing how the time intervals were determined.
TRTtwitch, the total reaction time for twich; PMTtwitch, pre-motor time for twitch; EMDtwitch, electromechanical delay for twitch.

Onset times for the M-wave and the force curve were defined in the same way as for MVC.

Statistical Analysis

All of parameters were analyzed using a paired t-test and these statistical analyses were performed with the assistance of Stat View ver. 4.5 software (SAS Institute Inc.). F ratios for the main effects and the interaction were considered significant at $p<0.05$. Descriptive statistics include means ± SD.

RESULTS

The femoral girth was significantly smaller on the involved side than on the uninvolved side at both AP10 (41.95 ± 3.13 cm on the involved side, 45.43 ± 3.13 cm on the uninvolved side; $F_{(1,18)}=118.20$, $p<0.01$) and AP15 (46.47 ± 3.66 cm on the involved side, 49.59 ± 3.16 cm on the uninvolved side; $F_{(1,18)}=98.86$, $p<0.01$).

Maximal isometric force was significantly decreased on the involved side than on the uninvolved side (107.01 ± 49.89 Nm on the involved side, 166.33 ± 42.06 Nm on the uninvolved side; $F_{(1,18)}=117.71$, $p<0.01$).

The differences in electromechanical properties for MVC and twitch response between both sides are summarized in Table 2. TRTmvc on the involved side was significantly prolonged than the uninvolved side ($F_{(1,18)}=6.804$, $p=0.018$). TRTtwitch was also significantly more prolonged on the involved side than in the other side ($F_{(1,18)}=5.738$, $p<0.028$). Neither PMTmvc nor PMTtwitch

Table 2. Comparison of electromechanical response among the four groups. (msec)

	involved side	uninvolved side
TRTmvc	251.47 ± 79.66 *	221.71 ± 47.92
TRTtwitch	26.12 ± 5.52 *	24.24 ± 6.20
PMTmvc	202.03 ± 81.72	191.89 ± 54.51
PMTtwitch	5.20 ± 2.70	4.65 ± 1.31
EMDmvc	53.42 ± 26.94 *	33.92 ± 13.51
EMDtwitch	20.04 ± 3.89 *	17.41 ± 2.81

*: significant difference, $p<0.05$

TRTmvc, the total reaction time for MVC; PMTmvc, pre-motor time for MVC; EMDmvc, electromechanical delay for MVC; TRTtwitch, the total reaction time for twitch; PMTtwitch, pre-motor time for twitch; EMDtwitch, electromechanical delay for twitch.

showed significant differences between both sides (PMTmvc; $F_{(1,18)}=0.509$, $p=0.485$ PMTtwitch; $F_{(3,70)}=2.35$, $p=0.08$). The mean of both EMDmvc and EMDtwitch on the involved side were significantly prolonged compared to the other sides (EMDmvc; $F_{(1,18)}=7.369$, $p=0.014$, EMDtwitch; $F_{(1,18)}=5.689$, $p=0.0225$).

Figure 3 shows plots of EMDmvc vs. EMDtwitch for both sides. The relationship was significant, however, the correlation was not very strong ($r=0.537$, $p<0.01$).

DISCUSSION

We hypothesized that reaction time to a sudden disturbance would be prolonged, not only because of impaired proprioception in the knee joint following ACL reconstruction, but also because of a prolonged processing interval in the central nervous system (CNS) and greater elasticity in the series elastic component of the quadriceps femoris. In passed studies[5,17], it was pointed out that the decrease of afferent input from proprioception of reconstructed ACL and articular cupsule resulted in prolonged and less accurate reaction. In other words, those precedence researches have put the focus only for the failure of the proprioception, not for disturbance of force producing process. In contrarily with passed studies, we tested the reaction time to visual stimulus and elicited by nerve electrical stimulation in order to separate the effect of peripheral proprioception from changes in CNS processing and transference of muscle force to the bone. Fig. 4 shows a graphical explanation of TRT, PMT, and EMD for both MVC and twitch. PMTmvc includes the CNS processing time for cognition of visual stimulus and motor programming, the interval of nerve conduction and transmission through spinal cord, as well as peripheral nerve conduction and transmission of action potentials to muscle. PMTtwitch measures the time interval of peripheral nerve conduction and transmission of action potentials to the muscle. Both EMDmvc and EMDtwitch include the time interval for muscle conduction of action potentials and in particular for transferring the muscular force to the bone. It has been suggested that EMD is associated predominantly with the time it takes to lengthen the elastic element[1,33]. This means that EMD is dependent largely on the function of the series elastic components[7]. The difference between EMDmvc and EMDtwitch is that EMDtwitch is produced by contraction of all motor units activated by the supramaximal stimulus, while EMDmvc is produced only by the voluntarily

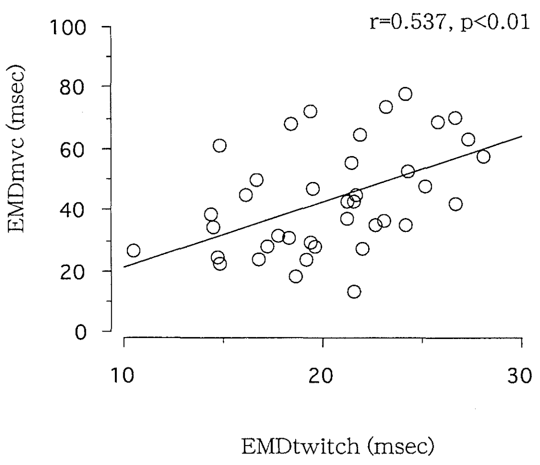

Fig. 3. Plots of EMDmvc vs. EMDtwitch
EMDmvc, electromechanical delay for MVC.
EMDtwitch, electromechanical delay for twitch.

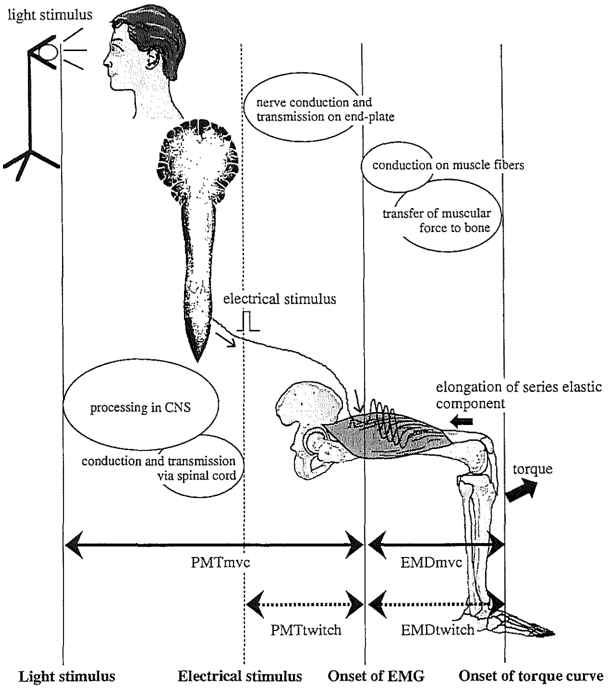

Fig. 4. A diagram for anatomical revel that each element targets.
PMTmvc, pre-motor time for MVC; EMDmvc, electromechanical delay for MVC; PMTtwitch, pre-motor time for twitch; EMDtwitch, electromechanical delay for twich; CNS, central nervous system.

available motor units. We interprete, therefore EMDmvc reflects not only the properties of the series elastic component, but also the quantity (e. g. how many motor units were recruited voluntarily) and quality (synchronization of motor units firing, what kind of motor units were recruited voluntarily) of voluntary muscle contraction. TRT for both MVC and twitch are constituted from total time interval of both PMT and EMD.

In this study, TRTmvc was prolonged on the involved side compaired with the uninvolved side. Two of the elements that contribute to TRTmvc, PMTmvc and PMTtwitch, were not significantly changed on the involved side compaired with uninvolved side. No change of PMTtwitch on the involved side established that the conduction velocity of the femoral nerve and the interval for transmission of the action potential from the site of electric stimulation to the muscle were not involved. This result supports Sale et al[23) who showed no change of motor nerve conduction velocity following immobilization. As a logical consequence, these results suggest that processing in the CNS was not prolonged. CNS processing time interval can be estimated by subtracting the peripheral conduction time interval from PMTmvc. Also these results show that PMTmvc was not a factor contributing to the prolongation of the reaction time on the involved side following disuse.

The reactoin time is known to be shorter as more fast muscle fibers type are present[21). Taylor et al showed that EMD is prolonged and muscle conduction velocity reduced by fatigue. On the basis of biopsy findings[28), the degree of these changes is greater for muscles with a higher percentage of type II fibers. They suggested that the prolongation of EMD is due to a reduction in the activity of type II fibers. Horita and Ishiko studied the relationship between muscle activity and metabolic state during intensive exercise of short duration and showed that EMD is prolonged due to changes in Excitation-Contraction coupling (E-C coupling) as a result of accumulation of materials such as lactate[12). Thus, EMD is considered to be a parameter reflecting qualitative elements, such as the properties of series viscoelastic components of the muscle, composition of the types of motor units participating in the activity, and E-C coupling. The influence of disuse on a latter element was reported by Arkhipenko et al who measured the change of Ca^{2+} transport by the skeletal muscle sarcoplasmic reticulum of rats after suspension of the hind limbs[3). Holy and Mounier indicated decrease in the apparent calcium binding constant of troponin C in rat muscles after spaceflight[11). The musculotendinous stiffness for rabbit soleus muscle-tendon unit has been confirmed to be decreased by immobilization[10). Widrick et al showed that the stiffness of soleus muscle of adult rat was decreased following 14 days of non-weight bearing[32,33). In the present study, EMDtwitch on the involved side was prolonged compared to the uninvolved sides. This result suggests three possibilities that adaptations such as decrease in the stiffness of series viscoelastic components, changes in peripheral muscle fiber composition to containing more slow type muscle fibers, or slower processing in E-C coupling occurred. These three physiological changes may have resulted in the prolonged EMDtwitch. Correlation between EMDtwitch and EMDmvc indicate that the three factors described above may have prolonged the EMDtwitch. Futhermore, this peripheral physiological disruption may, in turn, have led to the prolonged EMDmvc as controlled by the CNS. However, since the correlation coefficient between EMDmvc and EMD twitch was not very strong, other factors may have influenced prolongation of EMDmvc. We assume that these other factors resulted from changes in central control (e. g. quantity of activation, amount of synchronization among motor units, etc.). These factors should be evaluated in future.

Furthermore, our results suggest that prolongation of EMDmvc was one of the factors explaining the prolongation of TRTmvc to visual stimuli. Clinically, the prolongation of TRTmvc may lead to disorders of reaction time for sudden disturbances. Therefore serial evaluation of the time course of recovery of such functions after surgery is needed. We estimate that improvement of peripheral stiffness of series elastic components will result in more normal TRTmvc. Because TRT and EMD in response to a visual stimulus are elements of the reaction time interval for sudden disturbances, the results of this study indicate that improvement of peripheral stiffness of series viscoelastic components should lead to the shortening of reaction time interval to sudden disturbances. And furthermore, because the kinetic energy created by muscle is transiently stored as strain energy in series elastic components[1), we assume that decreased stiffness of series elastic components results partially in the decrease of maximal force.

In the near future, we are going to pursue a long-term study to evaluate the effect of recovery on these mechanisms.

CONCLUSION

These findings suggest that prolonged TRTmvc to visual stimulus in atrophied human quadriceps femoris muscle on the involved side of ACL reconstructed patients was principally caused by the prolongation of EMDmvc. Thus, the prolongation of reaction time following disuse was due to not only impaired proprioception, but also increased peripheral muscle compliance. The prolonged EMDmvc was most likely due to peripheral physiological changes; in particular, a decrease of the stiffness on the series elastic component, which was shown to be responsible for the prolongation of EMDtwitch. However, the correlation coefficient between EMDmvc and EMDtwitch might indicate that other factors also influenced the prolongation of EMDmvc.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the advice of K. Ogata, and technical assistance from H. Nakamura.

(Received July 24, 2000)
(Accepted October 23, 2000)

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