Time Course of Tension Development of Knee Extensor Muscle on Twitch, Tetanic, and Fast Voluntary Contraction in Normal Subjects

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TSUJI, I. and NAKAMURA, R. Time Course of Tension Development of Knee Extensor Muscle on Twitch, Tetanic, and Fast Voluntary Contraction in Normal Subjects. Tohoku J. exp. Med., 1988, 155 (3), 225-232 —— Tension lag time (TLT), a latency from the onset of electromyographic activities of prime mover muscle to the rise of tension, of knee extensor muscle was measured at twitch, tetanic, and fast voluntary contraction in three normal subjects. Twitch and tetanic contractions were evoked by four different strengths of electrical stimuli, and the peak tensions attained at fast voluntary contraction were within the range of tensions evoked by electrical stimulation. In each mode of contraction, the relationship between TLT and peak tension ($F_{\text{max}}$) was approximated by a hyperbolic function of $F_{\text{max}} (\text{TLT} - a) = b$. TLT was influenced by three factors: (1) $F_{\text{max}}$, the greater $F_{\text{max}}$, the shorter TLT; (2) force detection level to point out timing of the rise of tension, the higher the level, the longer TLT was; and (3) the mode of contraction, shortest at the twitch, longest at the voluntary, and intermediate in the tetanic contraction.

At the initiation of fast voluntary movement of a limb, there is a latency from the onset of electromyographic (EMG) activities of a prime mover muscle to the rise of tension, which is referred to as the electromechanical delay (EMD) (Komi 1979) or as the tension lag time (TLT) (Nakamura et al. 1984). It has been known that EMD or TLT is influenced by the force output; for instance, EMD of the knee extensor and the elbow flexor and extensor muscles correlated with the maximum force in normal subjects (Viitasalo and Komi 1981; Bell and Jacobs 1986), and TLT of the rectus femoris muscle of patients with cerebral hemiparesis were longer at the paretic than at the non-paretic side (Tsuji and Nakamura 1987).

There are, however, considerable differences in TLT of the knee extensor at 90 degrees flexion of the knee in normal subjects by different authors, i.e., 50.7+/−7.1 msec (Morris and Beaudet 1980), 38.3+/−8.3 msec (Viitasalo and Komi 1981), and 33.7+/−7.4 msec (Nakamura and Tsuji 1986). It seems that these variations are not only due to the differences in the force among the subjects

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examined but also due to the differences of force detection level to point out the timing of rise of tension.

In the present study, TLT was measured at four different force detection levels during twitch, tetanic, and fast voluntary contraction of the knee extensor muscle, to examine how TLT was influenced by both the force detection levels and the peak force produced, and whether TLT was different between the three modes of contraction at a similar range of peak force.

**METHOD**

Three healthy males aged from 29 to 32 years participated with informed consent in the study. The subject sat on a chair with the trunk upright and the hip and knee flexed at 90 degrees (Fig. 1). In order to measure isometric tension of the left knee extensor muscle, a strap was attached at 35 cm distal to the medial joint space of the left knee and was pulled with two ropes which were connected posteriorly with a load cell (U3B1-B, NMB Inc., Tokyo) and anteriorly with a 1 kg weight through a pulley so as to keep the ropes tense. The maximum output of the load cell was 10 kg and its nonlinearity was 0.05% of the rated output. Output of the load cell was DC amplified (6M92, Nihondenki San-ei, Tokyo) and fed to a microcomputer (PC-9801F, NEC, Tokyo) via an A/D converter with a sampling frequency of 1 kHz, and displayed on the CRT. Accuracy of the measurement was below 0.01 kg, as tested by calibration with external loads.

*Electrically evoked contraction*

Twitch contraction of the left rectus femoris muscle was evoked by a DC stimulator (SS102J, Nihon-koden, Tokyo) via 2 pad electrodes, one (4 × 4 cm) placed over the motor point of the left rectus femoris muscle and the other (3 × 3 cm) over the left patella. The stimulus pulse was a square wave of 1 msec duration with four different currents from 35 to 50 mA, respectively (Table 1). Three trials for each current were performed with intertrial intervals more than 30 sec. The lowest current of stimulus was first given, then the next higher current followed. After examining the twitch contractions, tetanic contraction evoked by 10 repetitive pulses of 200 Hz was examined with the same procedure as above. Four different intensities of stimuli ranged from 23.0 to 34.0 mA were delivered to make the muscle develop similar peak forces to those in the twitch contractions (Table 1).
The fast voluntary contraction

The subject was asked to extend the left knee as fast as possible responding a sound signal (1 kHz, 50 msec duration) presented 2 sec after a warning signal. The subject was requested to develop the tensions to match those evoked by the electric stimulations. Twenty trials were performed with intertrial intervals more than 30 sec. EMG activity of the left rectus femoris muscle was taken with surface electrodes, amplified and fed to the microcomputer, and displayed on the CRT. The experiment on the fast voluntary contractions was performed on a different day from that of the electrically evoked contractions.

Table 1. Stimulus intensity and mean $F_{\text{max}}$ at twitch and tetanic contractions in three subjects (M.F., I.T., and G.I.)

<table>
<thead>
<tr>
<th>Intensity (mA)</th>
<th>Twitch contraction</th>
<th></th>
<th></th>
<th>Tetanic contraction</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_{\text{max}}$ (kg)</td>
<td>M.F.</td>
<td>I.T.</td>
<td>G.I.</td>
<td>M.F.</td>
<td>I.T.</td>
</tr>
<tr>
<td>35</td>
<td>0.07</td>
<td>0.43</td>
<td>0.14</td>
<td>24.5</td>
<td>0.08</td>
<td>0.48</td>
</tr>
<tr>
<td>40</td>
<td>0.33</td>
<td>0.73</td>
<td>0.31</td>
<td>30.5</td>
<td>0.31</td>
<td>0.76</td>
</tr>
<tr>
<td>45</td>
<td>0.78</td>
<td>1.41</td>
<td>0.61</td>
<td>32.0</td>
<td>0.81</td>
<td>1.43</td>
</tr>
<tr>
<td>50</td>
<td>1.35</td>
<td>2.57</td>
<td>0.79</td>
<td>34.0</td>
<td>1.33</td>
<td>2.59</td>
</tr>
</tbody>
</table>

Fig. 2. Schematic presentation of the three variables measured: $F_{\text{max}}$ (the peak force), TLT (tension lag time), and CT (contraction time).
Fig. 2 presents schematically three variables measured in the both experiments: the peak force ($F_{\text{max}}$), TLT which was a latency from electrical stimulation or the onset of EMG activities to the force detection levels of 20, 50, 100 and 200 g, and contraction time (CT) which was the duration from the electrical stimulation or the onset of EMG activities to $F_{\text{max}}$.

RESULTS

Table 1 presents the intensity of stimulus and the mean $F_{\text{max}}$ of each subject during the twitch and tetanic contractions. Fig. 3 illustrates the scatter plots of $F_{\text{max}}$ versus TLT at 20 g of force detection level of a subject. In each mode of contraction, the invariable relationship between TLT and $F_{\text{max}}$ was observed, that is, TLT shortened with increasing $F_{\text{max}}$ when $F_{\text{max}}$ was small and became rather constant when $F_{\text{max}}$ exceeded about 1 kg. The relationship between TLT and $F_{\text{max}}$ is well approximated by a hyperbolic function of the equation $F_{\text{max}}(\text{TLT}-a)=b$, in which ‘a’ has the dimension of time and ‘b’ has the dimension of momentum. The value of ‘a’ is the asymptote of the equation. Table 2 shows the values of ‘a’ and ‘b’ of the equation at four force detection levels of every subject for three modes of contraction. Both ‘a’ and ‘b’, in each kind of contraction, increased as the force detection level elevated.

The values of ‘a’ were related with the mode of contractions when the force detection level was matched: Smallest at the twitch, largest at the voluntary, and intermediate at the tetanic contraction (Table 2). Fig. 4 shows the curves which plot the mean values of ‘a’ of three subjects and the corresponding levels of force detection for three modes of contractions. The slopes of the rise of tension were different between the three modes of muscle contractions even in the very early phase of tension development: Highest at the twitch, lowest at the voluntary, and

![Figure 3](image_url)  
Fig. 3. Scatter plots of TLT versus $F_{\text{max}}$ in the twitch (○), tetanic (●), and voluntary (∆) contractions. Abscissa: $F_{\text{max}}$ (kg) and ordinate: TLT (msec).
intermediate at the tetanic contraction, indicating that the difference of TLT resulted from the difference of the slope of the rise of tension.

Fig. 5 illustrates the scatter plots of $F_{\text{max}}$ versus CT of a subject on each mode of muscle contraction. CT was constant irrespective of $F_{\text{max}}$ attained in the present study. Table 3 shows mean CTs for each mode of contraction. CTs for twitch contraction were evaluated by two-way (stimulus $\times$ subject) analysis of variance. There was a significant main effect of subject ($p<0.01$) but not of stimulus. Also the interaction was significant ($p<0.01$). Accordingly, CT for the twitch contraction was constant irrespective of $F_{\text{max}}$ examined in the present study. It was also true in the tetanic contraction, for the same analysis as above indicated the significant main effect of subject ($p<0.01$) but neither the main effect of stimulus nor the interaction was significant. On the voluntary contraction, there was no significant correlation between $F_{\text{max}}$ and CT in any subject.
Thus, at each mode of contraction, CT of each subject was constant in the range of $F_{\text{max}}$ produced here. The relation of CT to the mode of contraction was examined by two-way (mode of contraction x subject) analysis of variance, which indicated significant main effects of mode of contraction ($p < 0.05$) and subject.

**Table 3.** Means and s.d.s (in parentheses) of CT of three subjects at twitch, tetanic, and voluntary contractions

<table>
<thead>
<tr>
<th>Mode</th>
<th>CT (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.F.</td>
<td>I.T.</td>
</tr>
<tr>
<td>Twitch</td>
<td>103.0 (3.5)</td>
</tr>
<tr>
<td>Tetanic</td>
<td>154.3 (4.5)</td>
</tr>
<tr>
<td>Voluntary</td>
<td>139.2 (5.2)</td>
</tr>
</tbody>
</table>

Thus, at each mode of contraction, CT of each subject was constant in the range of $F_{\text{max}}$ produced here. The relation of CT to the mode of contraction was examined by two-way (mode of contraction x subject) analysis of variance, which indicated significant main effects of mode of contraction ($p < 0.05$) and subject.
(p < 0.01) and significant interaction (p < 0.01). In all subjects, CT of twitch was shorter than those of tetanic and voluntary contractions. The relationship between CTs of tetanic and voluntary contractions was variable among the subjects. As compared with CT of voluntary contraction, CT of tetanic contraction was shorter in the subject I.T., longer in M.F., and not different in G.I.

**DISCUSSION**

The present results indicated that TLT was influenced by three factors: F\text{max}, the force detection level, and the mode of muscular contraction.

TLT depended on F\text{max} in each kind of muscle contraction. TLT shortened with increasing F\text{max} up to a certain level of F\text{max}. However, beyond this level, the increase in F\text{max} accompanied no further shortening of TLT consequently producing a plateau response in TLT. The relationship between TLT and F\text{max} is well approximated by a hyperbolic function of \( F\text{max} (\text{TLT} - a) = b \). The value of ‘a’ of this equation is the asymptotic value of TLT. One may consider ‘a’ as the ideal TLT because it minimally includes the early phase of tension development. As described above, TLT plateaus when F\text{max} exceeds a certain level. The F\text{max} level is related with ‘b’ because it is derived from the above equation that TLT should be \((a + 2)\) msec when F\text{max} is 1/2 ‘b’, and the variability of TLT should be less than 2 msec when F\text{max} exceeds 1/2 ‘b’.

TLT was also influenced by the force detection level. As indicated in Table 2, both ‘a’ and ‘b’ became larger as the force detection level elevated. The difference of ‘a’ between the force detection levels represents the time for the muscular tension to attain the corresponding level of force detection. Consequently, as the force detection level is elevated, the variability in TLT increases.

Measurement of the timing of the rise of tension (TLT) necessitates a set level of force detection. Based on the present result, the force detection level should be as low as possible, and TLT should be defined as the asymptotic value of the above equation at a particular force detection level.

Both TLT and CT depended on the mode of muscle contractions. The difference in the duration of the muscle activation accounts for the difference of CTs between the modes of contraction. The dependency of TLT on the mode of contraction is attributable to the difference of the slope of the rise of tension. Because it was observed that the slope of the rise of tension was different between the modes of muscle contractions (Fig. 3): Highest at twitch, lowest at voluntary, and intermediate at tetanic contraction.

It seems that several mechanisms would be responsible for the different slopes of the rise of tension between the modes of muscle contractions. First, the type of activated muscle fibres is different between the electrically evoked and the voluntary contractions. The threshold for excitation of muscle fibres to the electrical stimulation is lower for larger fibres whereas smaller fibre is first recruited during voluntary contractions. The size of the muscle fibre is related with the
tetanic tension and the speed of contraction, i.e., the larger the size of fibre, the larger its tension output and the faster the speed of contraction (Henneman 1980). Second, in the present study, the number of activated muscle fibres was smaller in the tetanic than in the twitch contraction, because the stimulus current applied to the muscle was lower in the tetanic than in the twitch contractions (Table 1). Third, at the tetanic contraction, the rate of tension development depends on the stimulation frequency. Buller and Lewis (1965) reported that, in the flexor hallucis longus muscle of the cat, the rate of tension development during tetanic stimulation increased with increase of stimulation frequency up to 300 Hz whereas the peak tension did not increase when the stimulation frequency exceeded 50 Hz. The dependency of the rate of tension development upon the firing frequency of the motor units would be also applicable to the voluntary muscle contraction, because the highest motor unit firing rate as much as that in the tetanic state induced by high-frequency stimulation was observed during rapid muscle contraction such as ballistic movement (Desmedt and Godaux 1978). The time for the muscular tension to attain a certain force detection level (TLT) shortens as the slope of the rise of tension becomes steeper. It is concluded that TLT would be determined in part by the slope of the rise of tension in the very early phase of tension development which in turn results from temporal and spatial pattern of muscle fibre activation.

References


