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A METHOD FOR ESTIMATING MECHANICAL PARAMETERS OF INTACT HUMAN MUSCLE

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ABSTRACT

A method of estimating mechanical parameters of the intact human muscle is proposed; force responses to ramp length perturbation of the muscle both at the resting and constant contracting states are compared with those of the model. The response during the short period (50ms) after the onset of the perturbation is used for the estimation. Time course of the length perturbation which could lead to the accurate estimation is determined by model analysis. Availability of this method is showed by applying it to the human thumb flexor muscle.

1. INTRODUCTION

A two-component model consisting of SEC (series elastic component) and CC (contractile component) which was proposed by A.V.Hill [1] has been widely accepted as the mechanical model of muscle. The property of CC is expressed by the force-velocity relation and the parallel elastic constant E_p (dynamics of the stretch-evoked activation mechanism). Since mechanical properties of the muscle contraction reflect the mechanism of contraction at molecular level, measurement of the mechanical parameters (series elastic constant E_s, parallel elastic constant E_p and dynamic constants of the force-velocity relation, a and b) is very important in the fields of muscle physiology, clinical medicine, physical science, bio-cybernetics and so forth. These mechanical parameters of the muscle isolated from animals have been determined by many workers. While there are several reports on mechanical properties of intact human muscle [2,3], the parameters have not been accurately estimated yet.

Estimation of the mechanical parameters is made by using dynamic relation between the applied length change and the measured force of the muscle. It has been well known that the muscle has nonlinear mechanical properties. Therefore, following properties ought to be considered for the estimation:

1) Elastic constants E_s and E_p are not constant and should vary with the level of the contractile force.

2) The force-velocity curve is not only the hyperbolic curve (the viscous coefficient changes with a change of the velocity of muscle length) but also dependent on the level of the contractile force.

Because of these properties, dynamic relations between the force and the length of muscle measured over the interval when the constant contractile force is maintained must be used for the estimation. Besides, with respect to the intact human muscle,

3) when the contracting muscle is stretched (or shortened), the variation of the contractile force is caused by the stretch reflex at the latency of 35 – 50ms.

Considering these properties, we made preliminary experiments and estimation of the mechanical parameters of the intact human muscles. In the experiments, the subject was asked to maintain a constant isometric force and then the muscle was ramp stretched. The force response over the interval of 50ms after the onset of stretch was used for the estimation. As a result, we recognized that mechanical parameters could not be easily estimated, because of the short period (50ms) of response used for the estimation and nonlinear properties of the muscle. It was also showed that sensitivities of the estimated parameters depended on time course of the applied length perturbation.

The purpose of this paper is, therefore, to propose a method of estimating the mechanical parameters of intact human muscle, and to show availability of this method by applying it to the intact human muscle (flexor pollicis longus muscle; FPL). For this purpose, we first attempt to determine the time course of length perturbation for accurate estimation of each parameter, with the aid of the computer simulation by using the mechanical model of the muscle.

2. MODEL ANALYSIS OF SENSITIVITY OF THE ESTIMATED PARAMETERS IN VARIOUS LENGTH PERTURBATIONS

There has been no definite answer to the question as to how the length perturbation of the muscle should be applied to the muscle for accurate estimation of the mechanical parameters of muscle. That is, the time course of ramp stretch or ramp shortening of the muscle which could lead to the accurate estimation of the parameters has not been determined yet. In order to determine the time course, computer simulations are made by using the mechanical model of muscle as follows. First, true values of the mechanical parameters are given, and force response of the muscle to the ramp stretch is calculated. Secondly, noise is added to the calculated force response, because the actually measured force response would involve noise. The force response thus finally obtained is referred to as an imitated force response in the present paper. Thirdly, mechanical parameters are estimated from the imitated force response with the aid of the model. Fourthly, the estimated parameters thus obtained are compared with the true values; sensitivity of the estimated parameters is investigated. This procedure is repeated with varying the time course of the length perturbation. Finally, conditions of the length perturbation necessary for the accurate estimation of the mechanical parameters are determined.

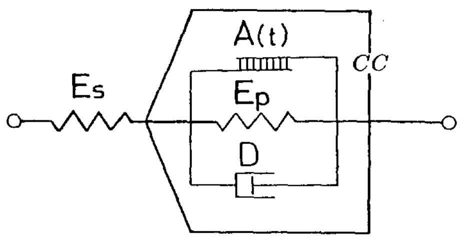

Fig.1 Mechanical model of muscle

2.1 Mechanical Model of Muscle

Figure 1 shows the mechanical model of muscle. Denoting the constant of the series elastic component by E_s and the length perturbation of the muscle by $\Delta L(t)$ as a function of time t, the force of the muscle f(t) is given by

$$f(t) = E_s(\Delta L(t) - x(t)) \tag{1}$$

where x(t) is the displacement of CC. Denoting the elastic constant of the parallel elastic component by E_p and the viscous constant of CC by D(t) and the contractile force of muscle by A(t), the force f(t) is

$$f(t) = E_p x(t) + D(t)\dot{x}(t) + A(t) \tag{2}$$

On the basis of the force-velocity relation, the viscous constant D(t) can be represented as follows [4]. When CC is stretched ($\dot{x}(t) = v_c \geq 0$),

$$D(t) = \frac{(a' + A_m)A(t)}{(b' + v_c)A_m} \tag{3}$$

and when CC is shortened ($v_c < 0$),

$$D(t) = \frac{(a + A_m)A(t)}{(b - v_c)A_m} \tag{4}$$

where a and a' are the heat constant, b and b' are the rate constant of energy liberation. These parameters are referred to as the dynamic constants. A_m is the maximum voluntary contractile force. The mechanical parameters of the muscle are thus E_s, E_p, a, a', b and b'. When the contractile force changes with time, E_s and E_p should be treated as a function of time. We simply treated them as the constant in the present study, because the response during the period when the constant contractile force was maintained was used for estimating the mechanical parameters.

2.2 Imitated Force Response

In order to calculate the imitated force response to ramp stretch, following mechanical parameters were employed referring to the values obtained from the muscle in animals; $Es = 33A_m/L_0, E_p = 4.5A_m/L_0, a/A_m = 0.25$ and $b/L_0 = 0.9/sec$, where L_0 is the natural muscle length. These values are those converted into the values at A(t)= $0.32A_m$.

Actually mechanical or electrical noise was involved in the experimentally measured force response. Further, estimation error was introduced into the force response of the muscle itself because estimated parameters of the passive components were not always correct (see 3.2). Therefore, such noise N(t) was added to the force response calculated from the model. Simply, composite of several sine waves of different frequencies was used as the noise;

$$N(t) = Q \sum_{i=1}^{7} p_i SIN w_i \tag{5}$$

where (p_i,w_i) was (0.3,0.25), (0.8,0.3), (0.6,0.42), (0.4,0.63), (0.2,6.28), (0.6,200) and (1,500), and Q is a parameter. The imitated force response $f_n(t)$ could be calculated by using Eqs. (1)-(5):

$$f_n(t) = f(t) + N(t) \tag{6}$$

NSR was used as an index of noise to signal ratio:

$$NSR = \frac{\int N(t)^2 dt}{\int f(t)^2 dt} \tag{7}$$

An example of the imitated response to ramp shortening is shown in Fig.2, where amount of the ramp shortening, Ld is $0.005L_0$ and the duration, Td is 10ms, and NSR is 0.0023.

2.3 Method of Estimating the Mechanical Parameters

The mechanical parameters of the muscle can be estimated as those by which a best fit is obtained between the imitated force response $f_n(t)$ and the model response f(t); this estimation can be accomplished in the way that optimal parameters are searched by minimizing the error between the imitated force response $f_n(t)$ and the model response f(t) with the aid of Simplex Method [5]. The error used in Simplex Method is the normalized integrated squared error;

$$ER = \int_{t_1}^{t_0} \frac{(f_n(t) - f(t))^2}{f(t)^2} dt \tag{8}$$

where t_0 is the onset of length perturbation and t_1 is the onset of the stretch reflex. Suppose that the contractile force A(t) maintains constant during the estimation period from t_0 to t_1.

While longer estimation period is desirable for more accurate estimation, such a limited period $t_0 - t_1$ ought to be taken because change of the contractile force occurs due to the stretch reflex caused by the length perturbation. The estimation period of 50ms was used in the present study, since it was showed by monitoring EMG that obvious change in the contractile force seemed to appear 60-70ms after the onset of stretch in human FPL muscle.

2.4 Method of Sensitivity Analysis

Basic idea of the sensitivity analysis of the estimated parameters is as follows. Suppose that the one mechanical parameter is changed from the estimated value to a certain value by a large amount, and other mechanical parameters are adjusted. If the model response of force thus obtained can still closely agree with the imitated force response, this estimated parameter is less reliable, or sensitivity of the estimated parameter is low. This idea was applied to individual mechanical parameters which were estimated at various length perturbations.

The procedure of the sensitivity analysis is explained by taking E_s as an example.

1) E_s is fixed at an arbitrary value around the estimated value. Minimum value of ER is searched by Simplex Method with adjusting other parameters except E_s.

2) This calculation is repeated by changing the value of E_s

3) The minimum values of ER thus obtained are plotted against E_s as (see Fig. 5A).

4) If the $ER - E_s$ curve is sharp around the extreme value, the estimated value of E_s is highly reliable, or with high sensitivity.

2.5 Simulation Results

The mechanical parameters were estimated by using the above mentioned method and the imitated force responses. Usefulness of the proposed estimation method was indicated by showing that the estimated parameters were almost the same as the true values and the model responses obtained from the estimated parameters closely agreed with the imitated responses. One example is shown Fig.2 shows.

Sensitivities of the estimated parameters calculated at various ramp perturbations are summarized in Table 1, where Ld is the amount of the ramp length perturbation and Td is the duration. Circles o represent the case where the mechanical parameter could be estimated with high sensitivity; the larger the circle is, the higher the sensitivity is. Crosses X represent the case of very low sensitivity, or less reliability. Table 1 is summarized as follows.

1) As to E_p, slow speed perturbation (Ld is small and Td is large) is necessary for more accurate estimation.

2) As to E_s, there is a specific range of Td and Ld for accurate estimation.

3) As to the dynamic constants, a and b, high speed perturbation (Ld is large and Td is small) is necessary for accurate estimation.

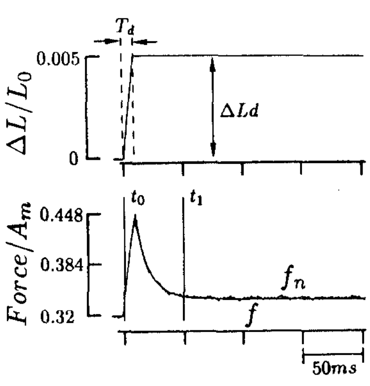

Fig.2 Model response(f) compared with the response(f_n) imitated at the values of parameters, $E_s = 33(A_m/L_0)$, $E_p = 4.5(A_m/L_0)$, $a/A_m = 0.25$ and $b/L_0 = 0.9/sec$. $\Delta Ld = 0.005L_0$ $Td = 5msec$ $t_0 \sim t_1$:period of estimation

Table 1 Result of analyzing sensitivity at various ΔLd and Td of shortening,

$\Delta Ld/L_0$	0.002			0.005			0.008			0.01		
$Td(ms)$	E_s	E_p	a,b	E_s	E_p	a,b	E_s	E_p	a,b	E_s	E_p	a,b
5	o	◯	×	◯	o	o	×	o	◯	×	o	◯
10	o	◯	×	◯	o	o	×	o	o	×	o	◯
15	o	◯	×	◯	o	×	×	o	×	×	o	×
20	o	◯	×	o	◯	×	×	◯	×	×	o	×
30	o	◯	×	o	◯	×	o	◯	×	×	◯	×

o is the case of high sensitivity, ◯ is the case of higher than o sensitivity and × is the case of bad sensitivity in estimation.

3. ESTIMATION OF THE MECHANICAL PARAMETERS OF HUMAN INTACT MUSCLE

3.1 Method of Experiment

The experimental setup is shown in Fig. 3. The subject sit down on a chair and placed his left hand and forearm on the horizontal stand. The forearm was pronated, and the wrist was fixed on the stand with leather belt. Both the hand and the thumb fundus were fixed with the mold made with thermoplastic impression compound (Kerr Ltd.), so that only the articulation of interphalangea pollicis could freely flex and extend. The tip of thumb was fixed with myo-print (Myo- Tronic Research INC.) in an aluminum box (28x30x30mm, thickness 2mm). The aluminum plate (45x20x2.5mm) was fixed on the box, and the tip of the plate was connected to a voice-coil type DC motor (Showa Densen Denran Co., Driving Force 8N/A) via the truck on a linear ball slide.

The force of the thumb was measured with strain-gauges affixed on the aluminum plate. Position, velocity and acceleration of the thumb movement were measured with sensors fixed on the truck. EMG activities of the flexor and extensor muscles were monitored with surface electrodes. All these measured variables were fed into a computer (PDP 11/23) via A/D converter (sampling interval, 1 ms). The position of DC motor, i.e., the position of thumb was controlled by the servo system including the computer.

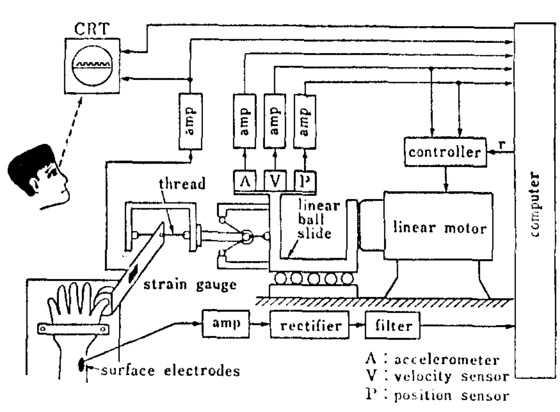

Fig.3 Experimetal setup

Experimental procedures were as follows. First, in order to estimate the parameters of the passive components and the measuring system, the thumb was ramp stretched at the resting state, when the subject was asked to relax both the flexor and extensor muscles. Secondly, in order to estimate the mechanical parameters of FPL, the thumb was also ramp stretched at the contracting state when the subject was developing the constant isometric force. The force developed by the thumb and the desired value were displayed on CRT. The subject was asked to maintain the constant desired force, watching CRT. These two types of experiments were repeated with changing the amount of stretch, Ld (3, 5, 7, 9mm) and the duration, Td (25, 40ms).

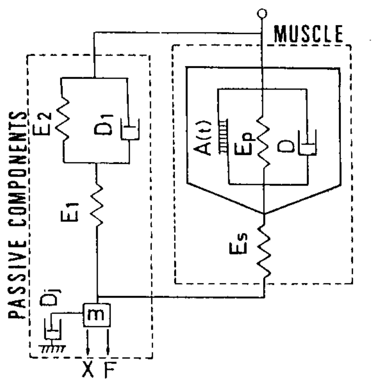

Fig.4 Mechanical model of skeltal muscle

3.2 Mechanical Model

Figure 4 shows the mechanical model employed for estimating the mechanical parameters of FPL. The passive components representing viscoelastic properties of the skin, connective tissue, blood, joint etc. and moment of inertia of the thumb and the measuring system (box and aluminum plate) were taken into account. Change of the joint angle was very small (about 3 to 9 degrees) in the present experiment, so that movement of the thumb was simply treated as a linear system. And the force and the displacement measured at the tip of the aluminum plate were used, in stead of the torque and the angle of the thumb.

The measured force F(t) is expressed by

$$F(t) = f_p(t) + f(t) \qquad (9)$$

where $f_p(t)$ is the force generated by the passive components and f(t) by the muscle. At the resting state, f(t)=0.

Denoting constants of the passive components in Fig. 9 as follows; elastic constants by E_1 and E_2, viscous constants by D_1 and D_j, and total mass of the thumb and the experimental equipment by m. When the muscle is stretched by the amount of $\Delta L(t)$, the force generated by the passive components is given as

$$f_p(t) = m\Delta \ddot{L}(t) + D_j \Delta \dot{L}(t) + E_1(\Delta L(t) - x_p(t)) \qquad (10)$$

$$E_1(\Delta L(t) - x_p(t)) = E_2 x_p(t) + D_1 x_p(t) \qquad (11)$$

Dynamic equations for the muscle (relation between f(t) and L(t)) at the contracting state are the same as Eqs. (1) – (4).

3.3 Method of Estimation

The parameters of passive components were estimated by using measured responses to ramp stretch at the resting state. The parameters were searched with Simplex method in the same way as being mentioned above that best fit between the measured force response and the model response could be obtained.

The mechanical parameters of the muscle were estimated by using the measured responses at the contracting state and the estimated parameters of the passive component. Method of the estimation was the same as explained in chapter 2; t_1= 50ms.

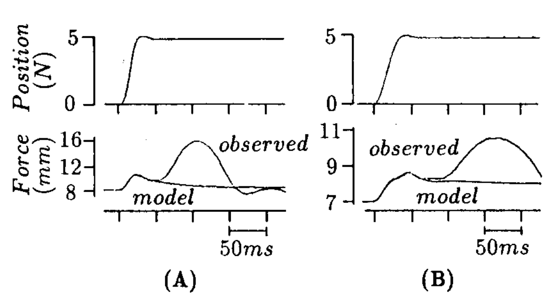

Fig.5 Comparision of model resonses with time courses of measured force at two type stretch
(A)Duration Td is about 25ms
(B)Duration Td is about 40ms

3.4 Result of Estimation

In Fig.5 is shown one example of the measured force and the model response obtained from the estimated parameters. In the experiment of (A), the velocity of ramp stretch was fast, the isometric force developed before the onset of stretch was about 8N (about 32 E_s=785(N/m), E_p=5.3(N/m), a'=21(N) and b'=0.32(m/s). In (B), the velocity was slow, the isometric force was about 7N. The estimated values were E_s=713(N/m), E_p=367(N/m), a'=0.41(N) and b'=0.43(m/s). Model responses closely agreed with the measured forces up to 50ms after the onset of stretch, as shown both in Figs. (A) and (B).

It was showed that E_s could be accurately estimated in the most of the length perturbations examined here; Td was 25, 40ms and Ld was 3, 5, and 7mm. An example of results of the sensitivity analysis is shown in Fig. 6A; this was obtained from the response of Fig. 5(A), and high sensitivity of E_s was indicated. Highest sensitivity was obtained at Td=25ms and Ld=5mm.

Accurate estimation of E_p was obtained only at the condition of Ld=5mm, Td=40ms. In Fig. 6B was shown the sensitivity of E_p obtained from the response of Fig. 4B; in this case, high sensitivity was demonstrated. Relations between minimum ER and E_p were examined for all the ramp perturbations studied, and it was showed that in the cases of the other ramp

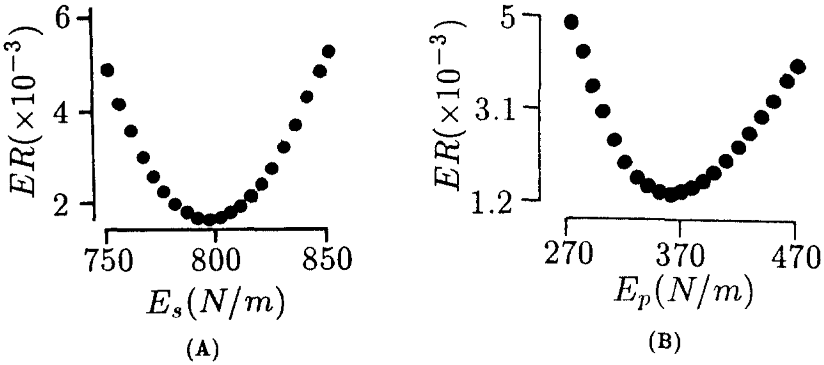

Fig.6 An example of results of sensitivity analysis

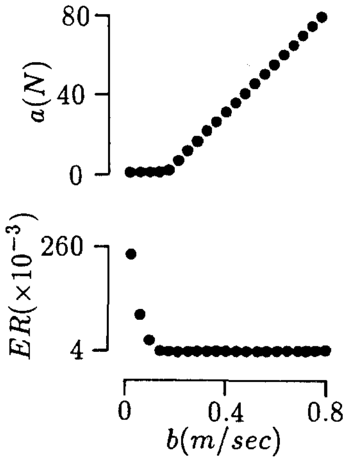

Fig.7 An example of analyzing sensitivity about the rate constant b of energy liberation, the upper is the relation between the rate constant b of energy liberation and the heat constant a and the lower is the ER.

perturbations except the condition of Ld=5mm and Td=40ms, sensitivities of E_p were very low. Individual parameters of the dynamic constants, a' and b' could not be estimated with high sensitivity. It was showed by the sensitivity analysis that a linear relation held between a' and b' when minimum ER was obtained. This is discussed in 3.5.

3.5 Estimation of Viscous Constant

Individual values of the dynamic constants, a' and b' could not be estimated with high sensitivity. It seemed to be due to slow speed of the stretch. Sensitivity analysis, however, could lead to a new idea that the coefficient corresponding to viscous constant could be estimated.

An example of the sensitivity analysis is shown in Fig.7. The lower figure shows relation between minimum ER and b', and the upper the relation between b' and a' at minimum ER. A linear relation between a' and b' was found at $b'1.0m/s$ (ER was almost minimum). This relation was expressed by $(a'+c)/b' = k$; k=132N·s/m and c= 22N were obtained from Fig. 7. Note that the parameter k corresponds to a coefficient of velocity-dependent force-loss of the contractile machinery, as explained below. When the contractile force is maximum A(t)=A_m and the velocity of CC is nearly zero ($v_c = dx/dt = 0$), viscous constant D(t) of Eq.(4) is expressed by

$$D = \frac{(a' + Am)}{b'} \tag{12}$$

where D is constant. This is the same relation as $k = (a' + c)/b'$. Consequently, it can be said that the value k obtained from the sensitivity analysis would correspond to the viscous constant at A(t)=A_m and v_c=0.

4. DISCUSSION

The present study has indicated that it is very difficult to estimate each mechanical parameter of the intact muscle with high sensitivity, and that it would be not only attributed to the nonlinear properties of the parameters depending either on the level of the contractile force or on the velocity of the muscle length, but also to the short interval (50ms) during which the muscle response can be used for estimation. This study has also proposed time courses of the length perturbation by which the mechanical parameters of the muscle could be estimated more accurately or with high sensitivity. This is of significant meaning in a practical sense.

Although results obtained from applying the present estimation method to human FPL muscle were not fully satisfactory, usefulness of the method and several important findings were indicated as being explained below.

1) Elastic constant of SEC, E_s could be accurately estimated in human FPL. With respect to the amount of ramp perturbation Ld and the duration Td for its accurate estimation, there was a relatively wide range (ramp perturbation; 3 to 7 degree, 25 to 50ms) which was the same as suggested by the model analysis.

2) It was suggested by the model analysis that elastic constant of PEC, E_p could be estimated accurately in

the case of lower speed length perturbation. This was showed in human FPL muscle. However, E_p could not be estimated accurately except the condition of Ld=5mm, Td=40ms at FPL. This differed obviously from the result of the model analysis, and the reason was not made clear by the present analysis yet.

3) The dynamic constants, a and b could not be estimated accurately in human FPL muscle. The reason was very clear; the FPL muscle could not be perturbed at sufficiently high speed with the present experimental setup, while the model analysis showed that fast speed perturbation was necessary for accurate estimation of the dynamic constants. However, it was indicated that the viscous constant at the maximum contractile force and zero velocity could be estimated with the sensitivity analysis, by using the results obtained from slow speed perturbation.

5. CONCLUSION

The present study showed an experimental method and an algorithm to estimate accurately the mechanical parameters of the intact human muscle. Usefulness of this estimation method was showed by applying it to human thumb flexor muscle (flexor pollicis longus; FPL). The results are summarized below.

1) Elastic constant of the series elastic component E_s could be estimated accurately in human FPL muscle. Range of 3 to 7 degree of ramp stretch during the duration of 25 to 50ms was available.

2) Slow speed perturbation was necessary for accurate estimation of the elastic constant of the parallel elastic component, E_p. The parameter E_p of human FPL could be accurately estimated only in the case of ramp stretch of 5 degree with the duration of 40ms.

3) Model analysis showed that high speed perturbation was necessary for accurately estimating the dynamic constants, a, a', b and b'. Due to the slow speed stretch, the dynamic constants of human FPL could not be estimated. However, the parameter k' corresponding to viscous constant at the maximum contractile force Am and zero velocity could be estimated as $k' = (a' + c)/b'$, where c was almost the same as A_m.

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