Effect of Muscle Length on Distribution of Muscle Fiber Conduction Velocity for M. Biceps Brachii

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Abstract. The influence of the muscle length on the distribution of muscle fiber conduction velocity (MFCV) was estimated at 3 different elbow angles (90°, 120° and 150°) during the contraction of 30% of isometric maximum voluntary contraction (MVC). Surface electromyogram was recorded in the distal region of m. biceps brachii using a surface array electrode. MFCVs at the different locations from the end-plate to the distal tendon of the muscle were measured directly using the averaging method. MFCVs near the end-plate and the distal tendon of the muscle showed the high values, while MFCVs in the middle region between the end-plate and the distal tendon of the muscle had low values at the same elbow angles. The mean MFCVs in the middle region decreased when the muscle length increased during the contraction of 30% MVC. The middle region length changed when the elbow joint was extended from the elbow angle of 90° to that of 150°. Although previous studies showed the influence of muscle length on MFCV for special regions (like end-plate, tendon, and middle region), MFCV for whole regions, that is, the distribution of MFCV has not been studied for various muscle length. The MFCV for the some region in the some muscle length could not be estimated. In the study, the distribution of MFCV in various muscle length for the contraction of 30% MVC was obtained, and the model with the function including muscle length for the estimation of MFCV was presented.

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Keywords: muscle length, conduction velocity, muscle fiber conduction velocity, elbow angle, isometric voluntary contraction

Introduction

Muscle fiber conduction velocity (MFCV) is a basic physiological index obtained from the myoelectric signal. Early attempts to measure MFCV in humans were made using intramuscular needle electrodes (Buchthal et al., 1955a and 1955b). Later, MFCV was investigated by noninvasive method using surface electrode (Lindström

et al., 1970). A number of studies of MFCV were published in recent years. Most of them had concentrated on the decreases of MFCV during sustained contraction and on the relationship between MFCV and the frequency of surface electromyogram (EMG) in power spectrum during the sustained contraction (Naeije and Zorn, 1982; Sadoyama et al., 1983; Arendt-Nielsen et al., 1989 and 1992). MFCV was concluded to be a new size principle parameter by Andreassen and Arendt-Nielsen (1987) who reported that the average MFCV increased with the increase of the contraction force. This attributed to the recruitment of motor unit (MU) that the larger MU with larger diameter had the higher conduction velocity as compared with the smaller MU.

Muscle fiber length in situ can change when the joint is rotated. Haines (1932 and 1934) reported that the length of the vastus intermedius muscle changed from 80 to 185 mm when the knee joint was rotated from the full extension position to the full flexion position. According to the core conductor model (Håkansson, 1957; Kossev et al., 1992), MFCV along muscle fibers was proportional to the square root of the muscle fiber radius. Consequently, a decline in MFCV would be expected with the stretch of muscle fiber. Håkansson (1957) found that the muscle fiber isolated for frog had various diameters. He also reported a linear relationship between the radius and MFCV. Gydikov and Kosarov (1973) investigated the influence of the length of the muscle on the shape of the action potential for m. biceps brachii using the surface multielectrode, and found that the variations in the angle of the elbow joint (i.e., elbow angle) had an essential influence on the shapes. But they also reported that MFCV was not essentially affected by the changes in the elbow angle. Morimoto (1986) studied the changes of the conduction velocity for single MUs of m. vastus medialis by passive length change. He reported that the muscle length increased by about 70% when changing the knee joint from full knee extension position to the full knee flexion position. Furthermore, in the change of knee angle the conduction velocity decreased by about 26%. Morimoto suggested that the decrease of MFCV along the muscle fibers was chiefly due to the decrease of the muscle fiber

diameter. Arendt-Nielsen et al. (1992) studied the influence of muscle length on MFCV. In their experiments, MFCVs were measured for *m. vastus lateralis* at the knee angles of 5, 45, 90, and 120° under various extension torques. They reported that the mean MFCV decreased significantly by approximately 1 m/s when the knee angle in flexion changed from 5° to 90°. They suggested that muscle length was an important parameter for MFCV. Kossev et al. (1992) studied the influence of the muscle length on the conduction velocity of the action potential in *m. biceps brachii*, and reported that MFCV decreased with the muscle elongation. Trontelj (1993) measured the changes of MFCV with muscle fiber length and reported that the maximum increase of MFCV was estimated to be 33% when muscle length of *m. orbicularis oculi* was shortened during the electrical stimulation. The averaged fiber diameter composition reflects the circumference of the muscle. A positive correlation between the mean MFCV and the circumference of the muscle was found (Stålberg, 1966; Broman et al., 1985). In all the above relationships between MFCV and muscle length, the values of MFCV for a location changes with the muscle length, and the values of MFCV were obtained to be constant value irrespective of the location on muscle surface for a constant muscle length.

The electrode distance from end-plate affected the estimates of MFCV. Placement of the surface electrodes over the end-plate could result in the large value of MFCV. The placement of the electrodes near the tendon generated also the large value of MFCV (Gydikov et al., 1976; Sollie et al., 1985). Roy et al. (1986) estimated MFCV and median frequency of EMG power spectrum as a function of electrode location on *tibialis anterior* muscle. They found that the values of MFCV were affected by the placement of both the innervation zone (end-plate) and the tendon, and reported that the largest values of the median frequency occurred near the end-plate and the tendon of the muscle, and decreased proportionally with distance from these areas. Also, they reported that MFCVs at different electrode locations on the same muscle were not constants. But, they did not found the distribution of MFCV.

Kaneko et al. (1990) investigated the influence of innervation zone on surface EMG signals. They proposed that the changes of MFCV affected the changes of EMG amplitude. Moreover, Gydikov and Kosarov (1972) had reported that the amplitudes of EMG signals for the different locations in the same muscle were different, and emphasized that the shapes of the impulses changed with the distance from the end-plate. Li and Sakamoto (1996a, and 1996b) showed that MFCV had a distribution from the end-plate to both the distal tendon and the proximal tendon along muscle fiber. In the study, MFCV along the length of fiber on the *m. biceps brachii* was measured during various contractions. MFCVs near the

end-plate or the tendons of the muscle fiber showed large values of about 10 m/s. However, MFCVs in the region of 20~45 mm from the end-plate to the both tendons of the muscle had an extremely narrow range of velocity during the contractions. The mean power frequency and the total power in EMG power spectrum were measured at different electrode locations on the *m. biceps brachii* during voluntary isometric contraction. The relationship between MFCV and EMG power spectrum was estimated during the contraction. It was noted that the values of mean power frequency, total power, and MFCV were related to the electrode location on the *m. biceps brachii*.

In this study, the purpose is to obtain the distribution of MFCV for the change of muscle length from the end-plate to the distal tendon of the *m. biceps brachii*. Hence, the model equation of MFCV for various muscle lengths was obtained.

Methods

Subjects and Experimental procedure

Experiments were carried out on 10 healthy male volunteers aged 20~23 yr. They were informed of the nature of the experimental procedure and consented to it. During the recording session, the subject was seated in a test chair. The hip joint was flexed to 90°. The different elbow angles (90, 120, and 150°) were maintained in the experiments. The rotation was aligned with the axis of rotation of the elbow joint. All experiments were performed under the condition of isometric contraction of *m. biceps brachii* (*caput breve*). The isometric maximum voluntary contractions (MVC) for the muscle were measured at elbow angles of 90, 120, and 150° which give the largest value of 3 brief maximal contractions. During the experiment, the muscle length between the distal tendon (distal end) and the proximal tendon (coracoid process of scapula) of the muscle were determined for every different elbow angle of joint (Kossev et al. 1992).

At the beginning of the experiment, the location of the end-plate was determined at different elbow angles during the contraction of 30% MVC. A typical example of average EMGs over the end-plate was shown in Fig. 1, in which the peaks of EMG signals around end-plate became inverse to each other, because EMG signals propagated to both tendons and the directions of propagation were opposite. The end-plate was decided by considering the difference between the times at peak levels of EMG for the neighboring two channels and the sign of EMG as the same way in the previous paper (Li and Sakamoto, 1996b). MFCV was determined in *m. biceps brachii* at 3 different elbow angles (90, 120, and 150°) during the contraction of 30% MVC. The degree of the contraction of 30% MVC was adopted because of the difficulty of muscular fatigue during the contraction in the experiment. The subject was asked to maintain the force of 30% MVC for 20 sec. EMG

recording was difficult in proximal region of the muscle because of the m. biceps brachii were divided into two parts (i.e., caput breve and caput longum) in proximal region, so that the measurement region was decided to be the location between end-plate and distal tendon of the muscle along the muscle fiber. The level of contraction force was displayed on an oscilloscope. The experiments with different conditions were performed on different days. The room temperature was maintained at 22-25°C.

EMG recording

Surface EMGs were recorded from m. biceps brachii at 3 different elbow angles during the contraction of 30% MVC. The surface electrode consisted of six stainless steel wires, 1 mm in diameter and 10 mm long. The distance of neighbour array interelectrodes was 5.0 mm. The array electrodes were assembled by referring to the design of Lynn (1979). The array electrodes were placed on the muscle surface and oriented perpendicularly to the direction along the muscle fibers. The skin was cleaned with alcohol. The EMG signals were amplified by a differential amplifier (NEC Sanei, Bioelectric AMPL-4124, 60 dB) with a bandwidth of 5.3 Hz to 1 KHz. The EMG signals were stored in a digital audio tape (SONY DT-120) using a data recorder (SONY, PC-108M).

Data analysis

MFCV was estimated by the averaging method (Nishizono et al., 1979). EMG signals were analyzed by the computer (NEC San-ei, Signal Processor 7T17). The EMG signals were presented with the use of averaging of EMG triggered as shown in Fig. 1. In the calculation the

time delay between the two signals with peak levels was obtained. The surface EMGs with a sampling time of 0.012 ms for 1024 data points that were averaged 50 times with the use of the averaging program were digitized. After manipulating the two scales for the EMG peaks on a cathode-ray tube, the time delay was analyzed automatically. As the distance between two recording electrodes De was known to be 5.0 mm, MFCV could be calculated directly in the unit of m/s with the use of the time delay T_s between the neighbouring EMGs (Li and Sakamoto, 1996b).

$$MFCV = De / T_s$$

(1)

Statistical analysis

The statistical significance of the difference between the muscle lengths and that between MFCVs were compared in all the different elbow angles (90, 120, and 150°) by means of t-test with the paired data. Results were considered statistically to be significant when the level of significance (p) was accepted to be equal to or less than 5%.

Results

The muscle length was defined to be the distance between the distal tendon and the proximal tendon of the muscle. The muscle length of m. biceps brachii was measured in all the different elbow angles when the load was not given to the test muscle. Figure 2 showed the relation between the muscle length and the elbow angle.

Fig. 1 Example of averaging EMG signals for four channels over end-plate obtained by triggering action potentials at the elbow angle of 90°.

Fig. 2 Relation between the muscle length and the angles of the elbow joint. The elbow joint at full extended position is defined to be 180°. ** $p < 0.01$.

Fig. 3 Distribution of muscle fiber conduction velocity at 3 different elbow angles during the contraction of 30% MVC. Le denotes the distance between the end-plate and the midpoint of neighbouring bipolar electrodes.

The muscle length increased when the elbow angle was extended from 90° to 150°. The mean muscle length of the ten subjects had a significant change when the elbow angles were increased from 90° to 120° and from 120° to 150°.

MFCVs in the region from the end-plate to the distal tendon of the muscle were estimated at 3 different elbow angles (90, 120, and 150°) during the contraction of 30% MVC. The distributions of MFCV from the end-plate to the distal tendon of the muscle were observed to be different

Fig. 4 Relation between the middle region length of the muscle and the elbow angles during the contraction of 30% MVC.

from that at the different elbow angles as shown in Fig. 3. The mean MFCVs at different electrode locations showed different values on m. biceps brachii. The mean value of MFCVs near both the end-plate and the distal tendon of the muscle showed large values up to 10 m/s. However, comparatively smaller values of MFCV around 4 m/s were obtained in the middle region between the end-plate and the distal tendon of the muscle in the different elbow angles. As shown in Fig. 3, there was a distribution of MFCVs over the region from the end-plate to the distal tendon, which ranged from the minimum value 4.11 ± 0.21 m/s to the maximum value 10.14 ± 1.13 m/s at the elbow angle of 90°. The distribution of MFCV ranged from 3.86 ± 0.18 m/s to 8.85 ± 0.86 m/s at the elbow angle of 120° and from 3.74 ± 0.19 m/s to 9.13 ± 1.06 m/s at the elbow angle of 150° for the same muscle contraction. This could be due to that MFCVs had an extremely different distribution at different elbow angles and that the middle region having the constant value of MFCV increased when the elbow angle increased.

The middle region length (MRL) having the constant MFCV around 4 m/s in Fig. 3 was estimated from the end-plate to the distal tendon of the muscle at the 3 different elbow angles. Figure 4 showed the mean MRLs for the ten subjects at different elbow angles during the contraction of 30% MVC. The mean MRL increased when the elbow angle was increased during voluntary isometric contraction. MRL changed from 30 mm to 40 mm when the elbow angle was increased from 90° to 120°. MRL increased from 40 mm to 45 mm when the elbow angle was increased from 120° to 150°. The reason for the

Fig. 5 The mean conduction velocity of different electrode locations calculated in the middle region of the muscle at 3 different elbow angles during the contraction of 30% MVC. * $p < 0.05$.

different MRLs at 3 different elbow angles was that the muscle length increased when the elbow angle increased.

MFCVs in the middle region were measured at different elbow angles of 90, 120, and 150 degrees during the contraction of 30% MVC. The mean MFCV in the middle region declined when the elbow angle increased during the same voluntary muscular contraction as shown in Fig. 5. Making use of the method of statistical t-test with the paired data, the significant difference of the mean MFCV was recognized when the elbow joint extended from the elbow angle of 90° to 120° and from 90° to 150°. The significant difference of MFCV was not recognized when the elbow joint extended from the elbow angle of 120° to 150° during the same contraction.

The relation between MFCV and the elbow angle near the end-plate and the distal tendon of the muscle was shown in Fig. 6. The mean MFCV of the ten subjects near the end-plate (i.e. 5 mm from end-plate) was found to decline when the elbow angle changed from 90° to 120° during the contraction of 30% MVC. MFCV near the end-plate had no significant changes when the elbow angle changed. The tendency of change of MFCV near the distal tendon of the muscle was not found when the elbow angle changed from 90° to 150° during the same muscular contraction.

Discussion

MFCVs at different locations of the electrodes in the distal region of the muscle were measured at different

Fig. 6 The muscle fiber conduction velocity measured near the end-plate and the distal tendon of the muscle at different elbow angles during the contraction of 30% MVC.

elbow angles (90, 120, and 150°) during the contraction of 30% MVC. It was found that MFCVs at the different locations from the end-plate to the distal tendon of the muscle were different during the same voluntary isometric contraction. MFCVs near the end-plate and the tendon of the muscle gave the largest values. Sollie et al. (1985) determined MFCV of m. biceps brachii with monopolar surface electrode. They reported that if the electrodes were placed too close to the end-plate or the distal tendon of the muscle, large values of MFCV would be found. Our results tend to be the same as the surface EMG results of Sollie's group. Roy et al. (1986) investigated the effect of electrode location on MFCV in tibialis anterior muscle. They reported that the large values of MFCVs were found near the distal tendon of the muscle in 8 out of 10 subjects. Also, Gydikov et al. (1976) studied EMG recorded by monopolar and bipolar leads from various motor units above the surface of the muscle, and they determined MFCV of different location on the m. triceps surae. They reported that MFCV in areas close to the end-plate and the tendon of the muscle denoted the large values on m. triceps surae. Li and Sakamoto (1996a) measured MFCV for different electrode locations on the m. biceps brachii during voluntary isometric contraction, and showed that MFCV near the end-plate and the tendon of the muscle had large values of MFCV, and found that the value of total power spectrum and mean power frequency were different along the direction of m. biceps brachii. Gydikov and Kosarov (1972) reported that the amplitudes of EMG signals at different locations in m.

biceps brachii were different, and expressed that the shape of the impulses changed with the electrode position. It was proposed that the changes of MFCV affected the changes of EMG amplitude (Kaneko et al. 1990). In the present study, the various values of MFCV along the muscle fiber were due to the different amplitudes of EMG signals at the various locations on the muscle.

The muscle fiber length of m. biceps brachii increased when the elbow angle was changed from 90° to 150° (Fig. 2). The result was in agreement with the results of the previous studies (Haines, 1932, 1934; Morimoto, 1986; Kossev et al., 1992). Furthermore, in this experiment, the different distributions of MFCV along the direction of the muscle fiber at the different elbow angles (90, 120, and 150°) during the contraction of 30% MVC were found. The mean MFCVs in the middle region of the muscle having a constant MFCV declined when the elbow angle increased during voluntary isometric contraction. It is worthwhile to note some studies concerning the nature of the variations of MFCV. When a muscle was stretched, the fiber diameter decreased and the conduction velocity along the muscle fiber declined (Håkansson, 1957). Gydikov and Kosarov (1973) reported that the variations in the muscle length of m. biceps brachii influenced the shapes of the action potential impulses when the elbow angles changed. The core conductor model suggested that MFCV changed by

Fig. 7 The Shape of the ensemble of muscle fibers for arbitrary elbow angle i .

the square root of the fiber radius (Håkansson, 1957; Kossev et al., 1992). The fiber diameter reflected the circumference of the muscle. A positive correlation between the mean MFCV and the circumference of the muscle fiber was reported by Stålberg (1966) and Broman et al. (1985). It was suggested that the resistance of the extracellular volume played a very important role in the conduction velocity (Buchthal et al., 1955a and 1955b). Also, they suggested that an increase in muscle length would increase the resistance and reduce MFCV. The different distributions of MFCV at different elbow angles was mainly attributable to the changes in the diameters of the muscle fibers.

EMG was obtained with surface electrode in the study, so that the action potential of many muscle fibers were measured. Hence, the ensemble of muscle fibers is supposed to have cone shape as shown in Fig. 7. The cone shape was already applied to the model for the mechanism of production of MFCV in the previous paper (Li and Sakamoto, 1996b). The volume of the cone is suppose to remain constant when the muscle length (l) changes. The following relation for cone's volume for the two kinds of muscle lengths, l_0 and, l_i are obtained.

$$2\pi a_0^2 \cdot (l_0/2) \cdot (1/3) = 2\pi a_i^2 \cdot (l_i/2) \cdot (1/3) \quad (2)$$

where a_0 and a_i are the radii of circle of the respective cone's base for the muscle lengths l_0 and l_i , respectively. The values with suffix 0 denote reference data of elbow angle 90°, and the values with suffix i denote data for arbitrary elbow angle. If MFCV is proportional to the square root of the diameter of ensemble of muscle fibers which Katz (1948) and Hodgkin and Huxley (1952) led in the study of conduction velocity of nerve and muscle, the following equation is used:

$$MFCV_i / MFCV_0 = (2a_i / 2a_0)^{1/2} \quad (3)$$

Using equation (2), the ratio of MFCV of equation (3) is expressed by the ratio of the muscle lengths:

$$MFCV_i / MFCV_0 = (l_0 / l_i)^{1/4} \quad (4)$$

In the study, the experimental mean value of $MFCV_0$ used here is 4.29 m/s for the muscle length 12.8 cm corresponding to elbow angle 90 degree, so the $MFCV_i$ muscle length for arbitrary elbow angle i (or muscle

Table 1 Estimated MFCV for 30% MVC

(a) elbow angle (degrees)	(b) muscle length* (cm)	(c) estimated MFCV+ (m/s)	(d) experimental MFCV** (m/s)	difference [(c)-(d)] (d) × 100 (%)
90	12.8	(4.29)	4.29	0.00
120	15.4	4.10	4.03	1.70
150	16.6	4.02	3.96	1.50

*see Fig. 2, $l_0=12.80$ cm in equation (4). **see Fig. 5. +MFCV for elbow angle of 120 or 150 degrees is estimated by equation (4), whereas $MFCV_0=4.29$ (m/s) and $l_0=12.8$ (cm) at the elbow angle of 90 degrees.

length l_i) could be evaluated with the use of equation (4) as shown in Table 1.

The estimated results of MFCVs are in good agreement with the experimental ones with the precision of less than a few percent. The result proves that the assumption of equation (3) in which MFCV is proportional to the square root of muscle diameter is reasonable.

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