2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Investigation of Motor Point Shift and Contraction Force of Triceps Brachii for Functional Electrical Stimulation

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Abstract— **Functional electrical stimulation (FES) has been used for neurorehabilitation of individuals with paralysis due to spinal cord injuries or stroke aftereffects. The biceps brachii is often adopted in studies on FES because of the ease of stimulation, while there are few studies on the triceps brachii. Stimulation of the triceps brachii is important because the biceps brachii tends to be spastic. The aim of this study is to investigate the position shift of the motor points (MPs) of the three main muscle groups in triceps brachii with respect to the elbow joint angle, and the contraction force of the muscle groups. Firstly, MPs were measured in 6 healthy individuals using an MP pen at 5 elbow joint angles. The MPs of the long and lateral heads shifted distally and laterally, and the MPs of the medial head shifted distally and medially as the arm extended. The MPs of the long head shifted farthest of all. Secondly, the contraction force was measured in 9 healthy individuals using a force gauge at elbow joint angle of 90 degrees. Three different voltages were applied: 4, 8, and 12 V. The results showed that the medial head yields a sufficient contraction force although the medial head is situated deeper than the other two muscle groups. These findings will help to better understand the stimulation of the triceps brachii and improve the efficiency of electrical stimulation therapy.**

I. Introduction

Paralysis due to spinal cord injury or stroke aftereffects causes muscle atrophy and contracture. In upper arm paralysis, the elbow joint loses mobility due to continuous contraction of the biceps brachii with progressive muscle atrophy of the triceps brachii. Paralysis negatively impacts activities for daily life, so early rehabilitation is recommended. Neuromuscular electrical stimulation (NMES), which activates paralyzed muscles with electrical stimulation, has been widely studied and applied for early the rehabilitation of paralysis [1]. Functional electrical stimulation (FES) that yields functional limb motion is one of the applications of NMES. The purpose of FES is to support and restore the motor functions [2][3].

The application of FES has two major problems. One is rapid muscle fatigue and the other is inaccurate limb control due to multiple stimulation [4]. In voluntary contractions, motor units are recruited gradually from small to large, which is described as Henneman's size principle. However, FES activates the motoneurons synchronously and recruits same subset of motor units repeatedly. This nonphysiological activation causes muscle fatigue and decline in the muscle contraction [5].

Spatially distributed sequential stimulation (SDSS) and motor point tracking stimulation (MPT) have been proposed to deal with these problems [6]-[8]. SDSS is a method of sending sequential stimulation pulses to each electrode with a phase shift of 90 degree [6]. This method is often compared to single electrode stimulation (SE). SE is a method of sending stimulation pulses through one active electrode. SDSS can activate different subset of motor units during stimulation, which is closer to physiological activation. SDSS requires a large placement area, which make it unsuitable for the stimulation of the upper arm which has multiple small muscles.

A proper position of stimulation electrodes is important for FES since it affects muscle contraction strength and pain [9]. Placing electrodes over the motor points (MPs) can maximize the contraction force and minimize the discomfort [10]. MP is defined as the skin area above the muscle where the least electrical stimulation evokes a visible muscle twitch [9][10]. The location of MPs is influenced by the muscle geometric structure, and MPs shift with muscle contraction. This means that the location of MPs is strongly associated with the joint angles [11]. MPT is a method of switching electrodes to follow the shift of MPs, and this method is applicable to small muscles in dynamic exercise. Kamihira et al. proposed 2 methods of MPT, one is time based shifting stimulation (TSS) and the other is joint angle based shifting stimulation (JASS) [7]. TSS is a method of periodically switching electrodes, and JASS is a method of switching electrodes based on joint angle. Kamihira et al. reported TSS produce a significantly better effect on the maintenance of muscle contraction. In addition, Ichikawa et al. reported increasing the density and selectivity of the MP tracking improve the stimulation efficiency [8].

The site of spastic muscles tends to be different in upper and lower limbs, with the extensor muscles in lower limb and the flexor muscles in upper limb. Flexor muscles had been thought to be important for improving paralysis of upper limb. However, Gowland et al. suggested that the weakness of antagonist muscles is associated with the muscle contracture [13]. Rehabilitation of extensor muscles in upper arm is important, while there are few studies on the triceps brachii than the biceps brachii due to the complex muscle structure. The triceps brachii consists of three muscle groups: the long, lateral, and medial heads. These muscle groups have same insertion, but the medial head is situated more medial to the upper arm than the other muscle groups. Although surface electrodes are often used for FES because of their low cost and high convenience, difficulty remains to deliver the stimulation to a deep point.

*This research was supported by JSPS KAKENHI Grant Numbers JP18H03761 and JP19K12877, a project commissioned by JSPS and NSFC under the Japan-China Scientific Cooperation Program.

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978-1-7281-1178-0/21/$31.00 ©2021 IEEE

It is necessary to investigate how the medial head of the triceps brachii contributes to contraction and whether a sufficient contraction force is available with FES. In addition, in order to apply FES to the triceps brachii, it is necessary to understand the structure of each muscle group and adjust the electrode position so that the target muscle group can be stimulated. Therefore, we searched for appropriate stimulation positions at multiple elbow joint angles, and investigated the contraction force of different muscle groups in triceps brachii.

II. MATERIALS AND METHODS

A. Motor Point Shift

Since the location of MPs is strongly associated with the joint angles, switching stimulation electrodes to follow the shift of MPs is necessary in upper arm rehabilitation. We investigated the location of the MPs of the triceps brachii at multiple elbow joint angles in order to perform upper arm rehabilitation with FES for elbow extension.

Subjects

Six healthy individuals (6 male, aged 20-22 years) participated in the experiment. The study was approved by the ethical board of the University of Electro-Communications. Written informed consent was obtained from all subjects before participation.

Searching Location of MPs

The location of MPs was determined relative to the arm length for each individual. Reference lines were made based on the method of Behringer [14] (Fig.1).

The horizontal reference line was defined as the circumference of the arm, and the vertical reference line was defined as a line connecting the elbow head and the acromion. We defined the elbow head as the origin, so the medial and proximal coordinates were in the positive direction. The horizontal and vertical reference lines were defined as X axis and Y axis. The location of the MPs, which was expressed X_{MP} and Y_{MP}, was defined as the relative value to the length of each reference line. The location of MP (X_{MP}, Y_{MP}) was calculated by:

$$X_{MP} = L_X / L_H \quad (1)$$

$$Y_{MP} = L_Y / L_V \quad (2)$$

The length of the horizontal and vertical reference lines was expressed as L_H and L_V, the distance from the MP to the Y axis and origin as L_X and L_Y.

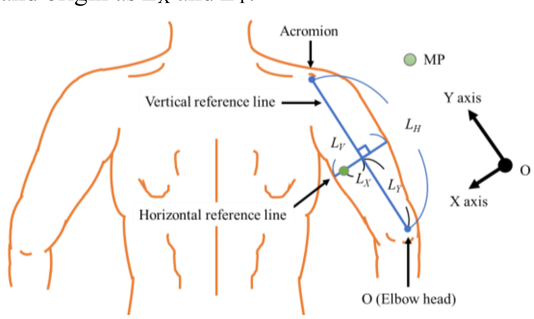

Fig 1. The reference lines and each length to calculate the location of the MPs seen from dorsal side.

Procedure

All subjects were seated on a chair with the right arm perpendicular to the frontal plane. The location of the MPs of the triceps brachii was explored at five elbow joint angles (0, 30, 60, 90 and 120 degree). We identified the MP that was the position where the most twitched by using an MP pen stimulator. The location of the MPs was explored 3 times at each angle and the average was calculated. During searching the MPs, all subjects exerted an equal load on the triceps brachii by pressing the push button switch. By pressing it, the contraction force was maintained at each joint angle during this experiment. The relationship between joint angles and the shift of the MP locations can be used in FES experiments with dynamic exercise. Finally, we made the reference lines and measured each length of L_H, L_V, L_X and L_Y.

Apparatus

The elbow joint angle was measured using a goniometer with a sampling frequency of 100 Hz (Model SG150 twin-axis goniometer; Biometric Ltd., UK). The location of MPs was explored by an MP pen stimulator (Compex Performance Muscle Stimulator Kit 6, Compex, USA). The push button switch (A30NL-MMM-TGA-P102-GA; Omron, Japan) with maximum operating load of 18N was used to exert an equal load.

B. Contraction Force

The triceps brachii consists of three muscle groups: the long, lateral, and medial heads. In FES, a certain target muscle is often stimulated, however, there are few studies investigating the contraction force of different muscle groups triceps brachii. We measured the contraction force of each muscle group and identified the muscle group that exerted the largest contraction force.

Subjects

Nine healthy individuals (9 male, aged 20-23 years) participated in the experiment. The study was approved by the ethical board of the University of Electro-Communications. Written informed consent was obtained from all subjects before participation.

Values to Evaluate Contraction force

Several values were defined to evaluate contraction force as shown in Fig. 2. F_{Base} was the mean force before stimulation. F_M and F_A were the difference from F_{Base} to the maximum and mean contraction forces. In this experiment, the contraction force induced by a stimulation over 1 second was measured.

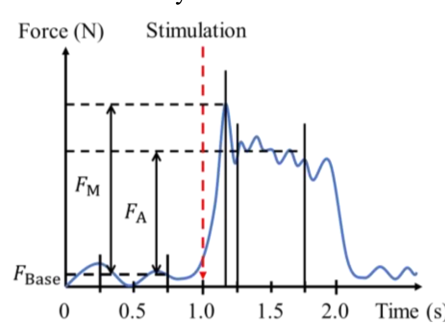

Fig 2. Definition of F_M, F_A and F_{Base}.

The mean contraction force was calculated using the values from 0.25 to 0.75 seconds. Defining these contraction forces in this way compensated for the effects of zero-point adjustment of a force gauge. The maximum and mean forces, defined as F_{MAX} and F_{AVE}, were determined relative to the maximum voluntary contraction (MVC).

$$F_{MAX} = F_M / F_{MVC} \tag{3}$$

$$F_{AVE} = F_A / F_{MVC} \tag{4}$$

Procedure

We identified the location of the MPs for an elbow joint angle of 90 degree using an MP pen. The location of all MPs was marked, and 2 electrodes were placed 2cm apart around the MP. For all subjects, their wrist and elbow joint were fixed, and we measured their MVC 3 times with a force gauge. MVC was measured for 1 second, and a rest period of a minute was required during each measurement. After the MVC measurement, we set a minimum rest of 3 minutes in consideration of muscle fatigue.

All subjects performed a warm-up protocol before the measurement of contraction forces to get used to the stimulation. The stimulation electrodes (diameter: 3.2 cm) were placed so that MP was in the center. These electrodes were placed vertical to the muscle bundle. During this protocol, each individual received 1 second of stimulation out of every 15 seconds. The voltage was set to 3, 5, and 7V, and we stimulated 3 times at each voltage. A minimum rest of three minutes was set after the warm-up protocol.

Finally, the measurement of the contraction force was conducted. Each individual received 1 second out of every 30 seconds. The voltage was set to 4, 8, and 12V, and we stimulated 3 times at each voltage. The contraction force was measured in order of medial, lateral and long heads. In this experiment, a burst modulation waveform with periodically interrupt of a high-frequency stimulation was used. The stimulation was alternating current with 2000Hz carrier frequency modulated at 100Hz (duty rate: 50%).

Apparatus

The elbow joint angle was measured using the goniometer described in the previous experiment. The contraction force was measured using a force gauge with a sampling frequency of 20 Hz (DST-500N, IMADA, Japan).

Data Analysis

The Wilcoxon signed rank test was performed to compare the contraction forces of muscle groups with a significance level of 0.05, corrected with the Bonferroni method.

III. Experimental Results

A. Motor Point Shift

Table 1 and Fig.3 show the position of the MPs of each muscle group at different elbow joint angles. Each color in Fig.3 corresponds to a joint angle.

The MPs of the lateral and long heads shifted distally and laterally as the elbow joint angles increased from 0 to 120 degrees. However, the MPs of the medial head shifted distally and medially. The vertical location of the MPs of the medial, lateral and long heads shifted approximately 2.18, 2.23 and 2.84 cm, respectively. The shifting distance of MPs differed for each angle interval. The MPs of the medial head shifted the longest from 0 to 30 degrees and of the lateral and long heads shifted from 30 to 60 degrees.

TABLE I. MP Positions at Different Elbow Joint Angles

Long head					
Angle (degree)	0	30	60	90	120
X_{MP} (%±SD)	31.5±1.5	29.8±1.4	29.0±1.6	29.2±2.6	28.0±2.9
Y_{MP} (%±SD)	38.6±2.4	36.5±2.2	32.7±2.4	30.8±2.5	30.3±2.3
Lateral head					
X_{MP} (%±SD)	6.5±1.8	4.8±2.3	3.3±3.0	3.7±2.6	4.6±2.5
Y_{MP} (%±SD)	40.1±3.1	37.6±3.5	35.0±4.2	34.0±4.1	33.5±4.3
Medial head					
X_{MP} (%±SD)	5.7±1.4	6.0±1.0	6.3±0.9	6.4±0.5	6.1±0.9
Y_{MP} (%±SD)	27.5±1.6	24.3±1.3	22.5±1.4	21.5±1.6	21.2±2.0

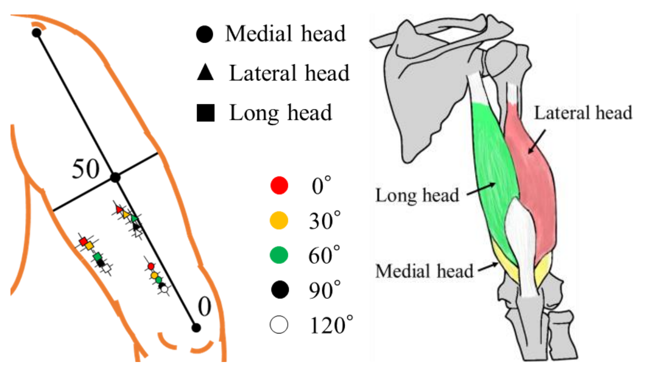

Fig 3. MP positions at each muscle group with respect to elbow joint angle [15]

Contraction Force

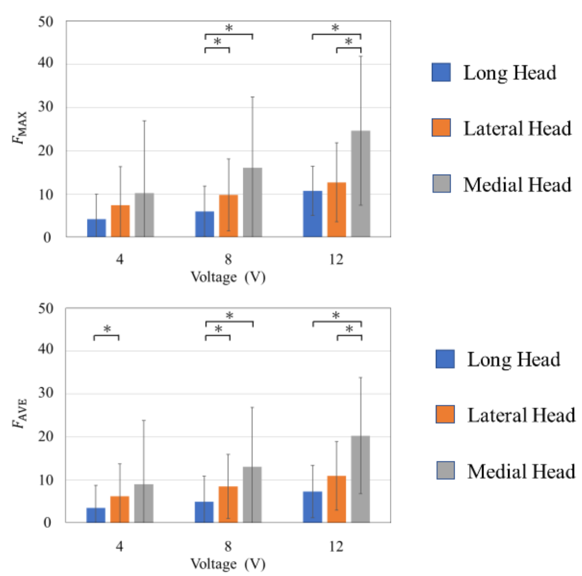

Fig 4. F_{MAX} and F_{AVE} of each muscle group at different voltage levels.

Fig.4 shows the maximum and mean contraction forces of each muscle group at different voltage levels. At all voltages, the contraction forces were in descending order of the medial, lateral and long heads. The lateral and medial heads exerted significantly larger contraction force F_{MAX} and F_{AVE} than the long head at 8V, and the medial head exerted significantly larger contraction force than the lateral and long heads at 12V. On the other hand, the lateral head output significantly larger F_{AVE} than the long head at 4V. Although there was no significant difference between the medial and lateral heads at 8V, the medial head output 1.67 and 1.55 times larger F_{MAX} and F_{AVE} than the lateral head.

IV. Discussion

A. Motor Point Shift

The MPs of all muscle groups shifted distally. The percentage of shifting of the MPs in the distal direction was larger than in the medial direction. The MPs shift when the muscle geometry changes due to flexion or extension. The MPs of the long head, which is the longest in the triceps brachii, shifted more than the other groups. In addition, the MPs of all muscle groups shifted parallel to the direction of the muscle fibers. This means that a muscle geometry may affect the amount and direction of MPs shifting. Since the triceps brachii muscle contracts as the elbow extends, there is a trend for increasing the shifting distance of the MPs from 0 to 60 degrees in all muscle groups. The constant contraction force was always exerted during this experiment by pushing the button, so this result represents the pure shifting amount of the MPs with a change of joint angles. It is expected that a shifting distance of MPs is related to contraction force because a strength of MVC depends on joint angles. In other words, a shifting distance of MPs will be maximum at the joint angle that exerts the greatest contraction force. Further investigation is needed to testify this hypothesis.

B. Contraction Force

The results show that the medial head output the largest F_{MAX} and F_{AVE} at all voltage levels. In particular, the medial head exerted significantly larger contraction force than the other groups at 12V. In addition, the medial head exerted larger contraction force although there was no significant difference between the medial and lateral heads. This result shows that FES yields sufficient contraction of the medial head even it is situated more medial to the upper arm than the other muscle groups. We noted that four in nine subjects output the largest F_{AVE} on the medial head at 4V. This result leaves us with the possibility that a low voltage cannot exert a sufficient contraction force at the medial head. Moreover, one in nine subjects exerted the largest contraction force on the lateral head at 12V. Simultaneous stimulation of the medial and lateral heads may be the best method to stimulus the triceps brachii, as it can reduce stimulation intensity and yield sufficient arm extension.

V. Conclusion

In this study, we investigated the location of MP of the triceps brachii at five elbow joint angles. The MPs of the lateral and long heads shifted distally and laterally, and the MPs of the medial head shifted distally and medially as an arm extends. Electrical stimulation considering MP shift may reduce muscle fatigue and minimizes discomfort. The medial head is deeper than the other two muscle groups, which makes it difficult to deliver stimulation via surface electrodes. However, the experimental results suggested the importance of applying FES to the medial head since the induced contraction force was the largest. Further study will conduct dynamic exercises of elbow extension by stimulating the triceps brachii according to the findings of this study.

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