

*Original Article***Consideration of ways to generate hip flexion torque by using electrical stimulation: Measurement of torque and the degree of pain**

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ABSTRACT

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Objective: To determine the best method to effectively generate hip flexion torque by using transcutaneous electrical stimulation in a fundamental study to restore the motor function of those with disabilities caused by central nervous system disorders.

Methods: Eleven healthy men participated in this study. Isometric hip flexion torque and the degree of pain during electrical stimulation were measured to determine the optimal stimulation site. The interferential frequency was 30 Hz. The duration of stimulation was 2 seconds, which was followed by a 15-second pause, and this was repeated 3 times. The electrodes were placed at 3 different sites: (1) on the sartorius and the tensor fasciae latae, (2) on the sartorius and the rectus femoris, and (3) on the rectus femoris and the tensor fasciae latae. The maximum tolerable intensity was determined for each of the 3 methods. Then the lowest current was used as the stimulus intensity for measurements. The contraction ratio was calculated by dividing the torque value of each individual muscle by the sum of the torque values of all muscles.

Results: The contraction ratio of the rectus femoris was significantly larger than that of the sartorius. Significant differences were not observed in the torque values or the degree of pain.

Conclusion: Electrical stimulation should be applied to the rectus femoris at the lowest stimulus intensity to produce the largest hip flexion torque.

Key words: transcutaneous electrical stimulation, functional electrical stimulation, hip flexion, torque, pain

Introduction

The most recent neurological research indicates the presence of brain plasticity in adults. Many studies have shown that neuromuscular electrical stimulation, which produces muscle contraction, is useful for the treatment of impairment caused by central nervous system damage.

Robbins et al. [1] conducted a meta-analysis of the literature published between 1966 and 2005 to determine the therapeutic effect of functional electrical stimulation (FES) on gait. Their report showed that FES effectively improved walking velocity. In the 2009 Japanese guidelines for stroke management, both FES of paralytic lower extremities and pedaling exercise were recommended additions to the usual rehabilitation measures because they were shown to effectively improve walking ability and muscle re-education [2].

In studies of transcutaneous FES applied to gait, 2 different methods have been used: single-channel stimulation and multi-channel stimulation. Single-channel stimulation was first reported in 1961 by Liberson et al. who corrected equinovarus foot during gait in stroke patients by electrical stimulation of the common peroneal nerve [3]. Similar methods were

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later used, and functional restoration could be acquired by use of the stimulator during and after intervention [4,5].

Trials using multi-channel stimulation by Bogataj et al. [6] showed that walking ability was improved by the stimulation of 6 muscles in the paralytic lower limbs of patients with subacute severe hemiplegia. Since then, transcutaneous FES has been proactively applied to gait exercise [7–9].

In previous studies, the gluteus maximus was stimulated for hip extension, the quadriceps femoris for knee extension, the hamstring for knee flexion, the common peroneal nerve or the tibialis anterior for dorsiflexion, and the gastrocnemius or soleus for plantar flexion [6–10]. However, there have been no reports on the use of transcutaneous FES to generate hip flexion. The reason is that the iliopsoas, the prime mover in hip joint flexion, is located too deep for direct stimulation by surface electrodes. The value of transcutaneous FES is that it stimulates superficial muscles. Therefore, to determine the best method to effectively generate hip flexion torque, the maximum isometric hip flexion torque (torque value) and the degree of pain generated using transcutaneous electrical stimulation with different electrode placements were compared.

Subjects and Methods

Eleven healthy young men with neither neurological nor orthopedic disabilities in their lower extremities or trunks participated in this study. The mean age (\pm standard deviation), height, and weight were 19.9 ± 1.3 years, 168.3 ± 3.9 cm, and 61.0 ± 5.8 kg, respectively. Prior to the study, its purpose and methods were sufficiently explained to the participants, and written informed consent was obtained from all the participants. Furthermore, the study was approved by the Research Ethics Committee of Kawasaki University of Medical Welfare (#154).

Torque was measured with a BIODEX SYSTEM3 dynamometer (SAKAI Medical Co. Ltd., Japan). Participants stood on a 10-cm-high platform, and the axis of the dynamometer coincided with the hip joint axis. Then, the participants were ordered to stand on their left leg, and the distal part of the right thigh was fixed to the attachment with the right leg raised above the floor (Figure 1). Although it is possible to measure torque while supine, the measurement was conducted while standing, without fixation of the trunk and pelvis, because our purpose was to generate the swing of the limb during gait.

Torque measurements were conducted 3 times, and each trial was based on the 3 different electrode placements described below. Participants rested for 150 seconds between each test. The 3 torque values acquired were averaged and analyzed. To determine the best stimulation site, after each measurement, the

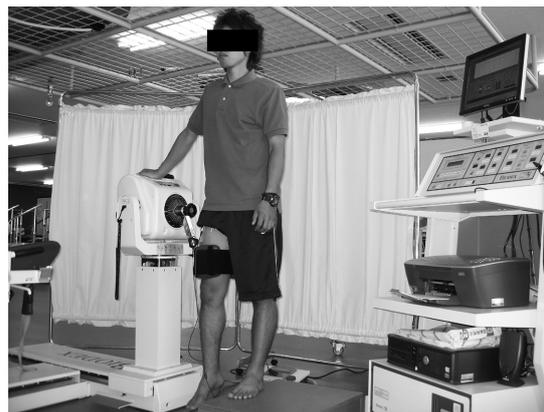


Figure 1. Torque value measurement

Participants stood on a 10-cm-high platform, and the axis of the dynamometer coincided with the hip joint axis. They were told to stand on their left leg, and the distal part of the right thigh was fixed to the attachment of the machine with the right leg raised above the floor.

degree of pain was evaluated on the Wong-Baker faces pain rating scale (face scale) [11]. The stimulation sequence under each condition was random. In a preliminary study, we confirmed that the most effective muscle contraction was generated by single channel alternating stimulation when the 2 electrodes were placed over individual motor points of 2 separate muscles. Therefore, the following 3 conditions were selected for electrode placement. Conditions:

- (1) The 2 electrodes were placed over individual motor points of the sartorius and the tensor fasciae latae (SA + TF).
- (2) The 2 electrodes were placed over individual motor points of the sartorius and the rectus femoris (SA + RF).
- (3) The 2 electrodes were placed over individual motor points of the rectus femoris and the tensor fasciae latae (RF + TF).

In order to determine the best placement for electrical stimulation, the motor points of the sartorius, the tensor fasciae latae, and the rectus femoris were determined using a chronaximeter (CX-3; OG Giken Co. Ltd., Japan) while supine.

Electrical stimulation was provided by a stimulator (ES-510; Ito Co. Ltd., Japan). Self-adhesive electrodes (5×9 cm) were used to decrease the pain felt by the stimulation of a relatively large area. The interferential carrier frequency was 5 kHz and the interferential frequency was 30 Hz. The duration of stimulation was 2 seconds, and stimulation was followed a 15-second rest, which was repeated 3 times. After the maximum tolerable intensity was determined for the 3 stimulation conditions by increasing the current by 5-mA intervals, the lowest value was selected as the stimulus intensity, and was used to measure the torque value for each participant.

To compare the reactivity of the sartorius, the tensor fasciae latae, and the rectus femoris at the same electrical stimulation intensity, the contraction ratio was calculated for each muscle from the acquired torque value. In this study, the contraction ratio was defined as the ratio per individual muscle per amount of muscle activity; it was assumed that all 3 muscles were being stimulated simultaneously. The calculation method is given by the following equation.

Contraction ratio of the relevant muscle (%) = (The sum of 2 torque values for the relevant muscle - the torque value without the relevant muscle)/the total

torque values of the 3 methods $\times 100$.

Statistical Analysis

For the statistical analysis, SPSS 15.0J for Windows (SPSS Japan Inc., Japan) was used. One-way repeated-measures analysis of variance (ANOVA) and the multiple comparison method were used to compare torque values and contraction ratios for the 3 conditions. The Kruskal–Wallis test was used to compare the degree of pain. A *P* value of <0.05 was considered statistically significant.

Table 1. Comparison of hip flexion torque values

	Electrode placement		
	SA + TF	SA + RF	RF + TF
Isometric torque (Nm)	8.3 \pm 3.4	8.6 \pm 3.7	9.8 \pm 4.1

SA + TF: stimulation of the sartorius and the tensor fasciae latae

SA + RF: stimulation of the sartorius and the rectus femoris

RF + TF: stimulation of the rectus femoris and the tensor fasciae latae

The data shown are the mean \pm SD.

Table 2. Comparison of the contraction ratios of individual muscles

	SA	TF	RF	<i>P</i> value	Multiple comparison
Contraction ratio (%)	26.3 \pm 7.6	34.7 \pm 10.9	39.0 \pm 9.0	< 0.05	RF $>$ SA

SA: sartorius, TF: tensor fasciae latae, RF: rectus femoris.

The data shown are the mean \pm SD.

Table 3. The degree of pain felt by individual participants and the means

Participant number	Electrode placement		
	SA + TF	SA + RF	RF + TF
1	2	4	3
2	3	3	2
3	3	3	2
4	2	3	2
5	3	3	3
6	4	4	4
7	1	3	3
8	1	2	1
9	2	3	3
10	2	2	3
11	2	3	3
mean \pm SD	2.3 \pm 0.9	3.0 \pm 0.6	2.6 \pm 0.8

SA + TF: stimulation of the sartorius and the tensor fasciae latae

SA + RF: stimulation of the sartorius and the rectus femoris

RF + TF: stimulation of the rectus femoris and the tensor fasciae latae

Evaluated by the face scale after the 3 measurements.

Results

The mean and standard deviation of the torque values in the 3 conditions are given in Table 1. The torque value for RF + TF (9.8 ± 4.1 Nm) was the largest, followed by SA + RF (8.6 ± 3.7 Nm), and SA + TF (8.3 ± 3.4 Nm). However, there were no significant differences between the individual conditions. The contraction ratio of the rectus femoris ($39.0 \pm 9.0\%$) was significantly larger than that of the sartorius ($26.3 \pm 7.6\%$) (Table 2). The degree of pain was lowest for SA + TF, followed by RF + TF, and SA + RF; however, there were no significant differences among the individual conditions. Ten of the 11 participants answered that the most painful condition was SA + RF, which indicates that stimulation of SA + RF was the most painful (Table 3).

Discussion

Transcutaneous electrical stimulation with surface electrodes effectively ameliorates motor dysfunction caused by cerebral disorders such as stroke and spinal cord injury, etc. However, in patients who have a normal sensory system, pain is induced by stimulating cutaneous nociceptors during muscle contraction [12–14]. Therefore, stimulus parameters, such as treatment time and intensity, inherently depend on the patient's pain tolerance. Our study determined the most suitable stimulation site at which pain was suppressed and the largest hip flexion torque was elicited. Three electrode placements; on the sartorius, the tensor fasciae latae, and the rectus femoris, were compared in terms of torque and pain generation. Because current below the maximum tolerable intensity was used as the stimulus intensity, it was possible to clarify the relationship between the stimulus site and the degree of pain.

Other important hip flexors that can be stimulated by surface electrodes include the pectineus and the adductor longus [15]. Those muscles were excluded because our pilot study showed that stimulation of the medial part of the thigh was extremely painful and caused remarkable hip adduction. In addition, the motor point in the pectineus is so close to the one in the adductor longus that attachment of electrodes on the individual muscles was impossible.

Although no significant differences in torque values were observed among the 3 electrode placements, the contraction ratio for the rectus femoris was significantly larger than that for the sartorius. These factors appear to be due to differences in electrical impedance or muscular resistance, because the same intensity of electrical stimulation was given at each site. When thick layers of high impedance tissue, such as adipose tissue, overlay low impedance tissue, such as nerves and muscles, higher current is required to depolarize these tissues [16]. This indicates that the amount of adipose tissue affects the contraction ratio.

Moreover, the electrical resistance of a geometrically homogeneous conductor is inversely proportional to the cross-sectional area and proportional to the length. Because the sartorius is the longest muscle in the human body [17], its resistance is higher than that of other muscles whose material compositions are similar. Therefore, the sartorius is considered to have the smallest contraction ratio.

Muscle torque can be obtained by multiplying the length of the moment arm by the strength of muscle contraction. When there is no difference in the muscle contraction strength of individual muscles, muscle torque is proportional to the length of the moment arm. Because the length of the moment arm in the rectus femoris on the sagittal plane is longer than that of the sartorius [15], it is highly likely that muscle torque in the rectus femoris is larger than that in the sartorius. Moreover, the traction force of the sartorius is 2 kgw, while that of the rectus femoris 5 kgw [18]. Therefore, the difference in absolute muscle force that can be estimated appears to affect the strength of muscle contraction during electrical stimulation. That is, the torque value in the rectus femoris is suggested to be larger because of the combined factors of the moment arm and the contraction force. Consequently, the contraction ratio for the rectus femoris appears to be larger than that for the sartorius.

An average hip flexion torque value produced by stimulation with electrodes implanted in 4 muscles (the tensor fasciae latae, the sartorius, the gracilis, and the rectus femoris) of patients with paraplegia was previously reported as 55 Nm [19]. In our study, a much smaller mean torque value of 8–10 Nm was produced. One reason for this difference might be the measuring method. In the previous studies, the pelvis was fixed in the supine position for the measurement. In contrast, our study was performed in the standing position without pelvic fixation. Because the muscles contracted with the distal part of the thigh fixed to the attachment, the phenomenon in which the proximal part tends to move towards the distal part, a so-called reverse action, might have occurred. This would have decreased the actual measured value. If the patient requires a knee-ankle-foot orthosis (KAFO) during gait training, its weight as well as the abnormal muscle tone would cause difficulty in hip flexion at the swing phase. Because the BIODEX is a device that measures joint torque, the joint must move during measurement. In our study, the actual torque value could be obtained at the zero-degree position of the hip joint for all the participants. Therefore, the strength of each torque was sufficient to flex the hip joint against gravity.

A comparison of the pain at the 3 electrical stimulation sites showed no significant differences in the face scale pain ratings; but, for most participants, the feeling of pain was greatest during SA + RF stimulation. This is indicative of differences in the pain felt among the 3 stimulus conditions. A study

with a larger number of participants, and an investigation of inter-electrode distance, are necessary for a detailed assessment of pain.

In conclusion, low intensity stimulation of the rectus femoris generated larger hip flexion torque than stimulation of the other muscles. However, it is noteworthy that the feeling of pain tended to increase when the electrodes were placed on the rectus femoris; and, in general, the greater the stimulus intensity, the stronger the feeling of pain. The possibility that strong muscle contraction itself may cause pain must be considered. When FES is applied, the existing sensory function needs to be examined. Clinical use of electrical stimulation to aid hip flexion must be applied to SA + TF when there is remaining sensory function. However, it should be applied to RF + TF when there is serious hypesthesia or anesthesia.

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