Use of Electrical or Magnetic Stimulation for Generating Hip Flexion Torque

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ABSTRACT

Objective: The purpose of this study was to investigate the most suitable site and method to effectively generate isometric hip flexion torque (torque value) using transcutaneous electrical or magnetic stimulation.

Design: Eleven healthy volunteers underwent torque value and pain degree measurements during magnetic stimulation of the iliopsoas using 3 coil placements. Following that, the peak torque values generated under 3 conditions of electrical stimulation of the sartorius, tensor fasciae latae, and rectus femoris, or that generated by magnetic stimulation of the iliopsoas were recorded at maximum tolerance intensity.

Results: No significant differences in torque values were observed among the 3 coil placements. Magnetic stimulation of a point below the inguinal ligament caused significantly more pain than the other points. Magnetic stimulation of the iliopsoas generated significantly higher torque values than electrical stimulation of the 2 hip flexor muscles together.

Conclusions: The hip joint was one of the most suitable regions for application of magnetic stimulation, as an alternative method to electrical stimulation.

Key Words: Magnetic Stimulation, Transcutaneous Electrical Stimulation, Torque, Pain

INTRODUCTION

The presence of brain plasticity in adults has been of particular interest in recent neurological research. Many studies have shown that neuromuscular electrical stimulation of muscles was a useful treatment for motor paralysis caused by central nervous system damage. The Japanese Guidelines for the Management of Stroke (2009) have recommended electrical stimulation as an adjunct therapy with the usual rehabilitation exercises, as a result of much evidence.[1]

Transcutaneous functional electrical stimulation (FES) techniques applied for improving gait are roughly divided into 2 trials: single-channel and multi-channel stimulation. Trials using single-channel stimulation primarily focused on controlling the peripheral ankle joint.[2, 3, 4] Patients with severe hemiplegia, who had low muscle tone, are excluded from application of single-channel stimulation. On the other hand, multi-channel stimulation technique was applied for restoring patient's walking ability and demonstrated several outstanding effects.[5-9] However, this method was not clinically widespread because of the technical difficulty in the control of multiple joints using only electrical stimulation. In addition, the stimulation apparatus was very large and expensive for use in clinical settings and skilled techniques were required to operate the stimulus system. These factors have prevented the application of this method in clinical sites. Transcutaneous FES has also fatal limitation that this method cannot contract the iliopsoas (IL), the prime mover of hip joint flexion, because the IL is located too deep to be directly stimulated by surface electrodes. Normal persons walking at their preferred speed may display no significant flexor muscle action after initiating the first step[10] while the patients with severe paralysis are likely to need more efforts to induce hip flexional motion because of the lack of pendulum movement in lower extremities. The IL which has the most extensive cross-sectional area in hip flexors is useful to induce hip flexion movement effectively.

Recently, some studies have reported the use of not only electrical stimulation but also magnetic stimulation as external stimulations for muscle contractions. The studies have described the application of magnetic stimulation of the lower extremities via the femoral nerve[11] or quadriceps femoris muscles[12, 13]; the knee extension torque was measured to investigate the effect of this new application. Although magnetic stimulation is minimally invasive and can induce inner muscle contraction, no reports have stated that it was useful for stimulating the IL, which generates hip flexion torque.

In the clinical gait training of severe hemiplegic patients, knee-ankle-foot orthoses (KAFO) are used to compensate for the loss of stability in the paralytic lower extremities, and therapists assist the swing of the paralyzed lower extremities using their own feet to compensate for the loss of voluntary movements. However, it is difficult for a therapist to precisely assist the swing of the paralyzed lower extremity during gait training because the amount of the therapist's assistance is sometimes excessive to keep a patient standing by him or herself. Circumduction gait with external rotation of the hip joint is a typical abnormal gait pattern for hemiplegic patients. External rotation of the hip joint is caused secondarily by posterior rotation of the pelvis in the stance phase and is thought to be a negative effect of motor learning.

Therapists must repeatedly provide normal movement patterns and avoid abnormal movement patterns as much as possible from the first exercise.

The present study provides fundamental research to assist the swing of paralyzed lower limbs and to model a normal swing pattern during gait training from the point of view that control of a proximal single joint using electrical or magnetic stimulation is practical. The purpose of this study was to determine the most suitable method to effectively generate hip flexion torque using external stimulation. Therefore, we first compared maximum isometric hip flexion torque (torque value) and the degree of pain in different coil placements for magnetic stimulation. Furthermore, we compared torque values generated by 3 electrical stimulations of the superficial hip flexor muscles with magnetic stimulation of the IL to determine the most suitable technique for hip flexion.

SUBJECTS AND METHODS

Measurement method of torque values

Eleven healthy young men with neither neurological nor orthopedic disabilities in their lower extremities and trunks participated in this study. The mean ± standard deviation values for age, height, and weight were 19.9 ± 1.3 years, 168.3 ± 3.9 cm, and 61.0 ± 5.8 kg, respectively. Before the study began, all participants were adequately explained the study's purpose and methods before participation, and each of them provided written informed consent. The study was approved by our institution's research ethics committee for human subjects.

After the identification of the stimulus sites for magnetic and electrical stimulation in the supine position as described below, torque values of the right hip flexors were randomly measured thrice in each participant during external stimulation. The participants rested for 2.5 min between individual tests. An isokinetic dynamometer (BIODEX SYSTEM 3; Sakai Medical Co. Ltd., Japan) was used to measure the torque value in the standing position (Figure 1).[14] The truncal forward and backward moments were prevented using a monitor of BIODEX SYSTEM3 as the feedback method of torque waves during rest period. The participants were ordered not to contract the hip flexors voluntarily during external stimulation. The averages of 3 torque values acquired from individual measurements were analyzed.

Determination of the most suitable site for magnetic stimulation

To determine the most suitable sites on the IL for magnetic stimulation, 3 stimulus points of the IL were selected according to the needle electrode insertion sites used in clinical electromyography[15] and palpation placement (Figure 2).[16] Point (1) and point (2) were located by palpation, and their midpoint was considered as point (3). Magnetic stimulation was administered by a repetitive magnetic stimulator (MagPro; Medtronic Inc., USA). A round magnetic coil with a 10-mm inner radius and a 60-mm outer radius (DANTEC Medical Inc., Denmark) was used. To inhibit coil heating during measurements, the stimulation frequency was set at 25 Hz with an on-time of 2 sec and an off-time of 15 sec. Since peak eddy current was reported to flow through near the center of the coil in the manufacturer’s instruction book, the center of the coil was placed on the 3 stimulus points of the IL and stuck to the skin surface as closely as possible. The site of nerve excitation was reported to depend on the direction of the nerve fibers and the coil geometry.[17, 18, 19] Accordingly, we examined optimal directions of the coil to get strong reactions and not to disturb the torque measurements. After the maximum tolerable intensity was determined for the 3 coil placements by increasing the intensity in 15-A/μs intervals, the lowest of the 3 intensities was selected for measurement of torque values. As a result, the stimulation intensity was set at 60 A/μs for all participants. Three times of stimulations were delivered at each placement of the coil. In addition, the degree of pain during magnetic stimulation was evaluated using the Wong-Baker FACES pain rating scale (face scale)[20] after each measurement. Face 5 indicated "hurts as much as you can imagine," whereas face 0 indicated "no hurt." To confirm whether the femoral nerve was excited or not by magnetic stimulation, we tried to record compound muscle action potentials (CMAPs) from the sartorius (SA) and the rectus femoris (RF) as a preliminary experiment. In fact, the amplitudes of CMAPs were detected on the recording electrodes placed on these muscles especially during the stimulation of point (1). Consequently, to generate the highest hip flexion torque had priority over other things in the current study.

Comparisons of electrical and magnetic stimulation

After the adequate placement of the coil was determined, the torque values generated by electrical and magnetic stimulation were compared. Electrical stimulation was delivered using a stimulator (ES-510; Ito Co. Ltd., Japan), after 2 self-adhesive electrodes (5 × 9 cm) were placed at 3 different conditions (Figure

3).[14] The motor points of the SA, RF, and tensor fasciae latae (TF) were previously searched for using another stimulator (CX-3; OG Giken Co. Ltd., Japan) in the supine position to determine the most contractible sites by electrical stimulation.

The parameters of the external stimulation procedure were frequency, 30 Hz; on-time, 2 sec; and off-time, 15 sec, as described by Han et al.[12] and Szecsi et al.[13] The intensity of each stimulation was increased in a stepwise manner in 5-mA increments for electrical stimulation and 15-A/μs increments for magnetic stimulation until the participants could no longer tolerate the pain (maximum tolerable intensity). The stimulus site of the IL, at which the maximum torque value was produced in the first half of the present study, was adopted as a representative IL site to compare torque values between electrical and magnetic stimulation. Prior to the torque measurement during magnetic stimulation, the torque measurements during electrical stimulation were conducted. The stimulation sequence under the 3 electrical stimulus conditions was random.

Statistical Analysis

SPSS 15.0J for Windows (SPSS Japan Inc., Japan) was used for statistical analysis. A one-way repeated-measures analysis of variance was used to compare torque values among the 3 coil placements and those between electrical and magnetic stimulation methods. The Friedman test was used to compare the degrees of pain experienced. The multiple comparison tests were performed when significant differences were found. Values of $P < 0.05$ were considered statistically significant.

RESULTS

Investigation of the most suitable site for magnetic stimulation

The individual torque value data obtained with the 3 coil placements are presented in Table 1. The mean torque values for point (3) were the highest, followed by point (1) and point (2). Peak torque was induced in 5 participants each at point (1) and point (3) and in 1 participant at point (2). Thus, there were no significant differences in torque values among the 3 coil placements (Table 2). With regard to the degree of pain, we found that magnetic stimulation of point (1) caused significantly more pain than that at point (2). However, significant differences were not observed among other stimulus sites (Table 2). The maximum pain ratio among all participants was face 4 (“hurts a whole lot”).

Comparisons of hip flexion torque generated by electrical and magnetic stimulation

Point (3) was selected as the site for magnetic stimulation of the IL. The mean torque value and standard deviation of SA + TF, SA + RF, RF + TF, and IL were 12.8 ± 6.0 Nm, 10.8 ± 4.4 Nm, 12.0 ± 4.4 Nm, and 19.2 ± 8.8 Nm, respectively (Table 3). Magnetic stimulation of the IL generated significantly higher torque values than electrical stimulation of the SA + RF, RF + TF ($P < 0.01$), and SA + TF ($P < 0.05$), although the pain induced by magnetic stimulation was same degree as that induced by electrical stimulation. No significant differences were noted among other conditions.

DISCUSSION

Investigation of the most suitable site for magnetic stimulation

Magnetic stimulation is known to induce eddy currents in vivo using time-varying magnetic fields and to excite nerves and muscles without stimulating skin nociceptors.[21, 22] In the present study, magnetic stimulation was used to contract the IL, which was difficult to stimulate by transcutaneous FES. Although the peak torque was generated in 5 participants at point (1) or point (3), it was generated in only 1 participant at point (2). Thus, no significant differences in torque values were observed among the 3 different coil placements. The femoral nerve runs between the psoas and the iliacus muscles in the proximal part of the inguinal ligament and reaches the anterior part of the thigh through the muscular space. It branches off and innervates the psoas major and iliacus in the minor pelvis.[23] Because the motor point of the IL is located in the upper part of the inguinal ligament, it was anticipated that point (2) or point (3) were suitable sites for coil placement in the case of IL stimulation. However, the torque value at point (2) tended to be lower than that at the other stimulation sites. Contraction of the rectus abdominis seemed to be stronger than that of the IL by observation because point (2) was the nearest position to the rectus abdominis and, moreover, might be the farthest position from the IL due to structural feature of pelvis. The rectus abdominis should be suppressed to contract in order not to cause new gait disturbance by use of magnetic stimulation. These causes therefore seemed to indicate that point (2) was the unsuitable site of stimulation.

Regarding the degree of pain, stimulation of point (1) was more likely to induce pain than the other points. The pain factor caused by magnetic stimulation directly stimulated some nociceptors: A-delta myelinated heat nociceptors and C-fiber nociceptors in the muscle, tendon, and fascia. Han et al.[12] and Szecsi et al.[13] have reported that magnetic stimulation caused not only muscle contraction but also some degree of stimulation-induced pain. The stimulus intensity of the thigh muscles reported in previous studies was higher than that of the lower abdomen reported in this study. This indicated that pain sensitivity varied with the stimulation site and that the number of nociceptors affected the degree of pain during magnetic stimulation. Therefore, it is assumed that the number of nociceptors under the epidermis of point (1) was higher than that of other stimulus points.

The round coil used in this study had a diameter of 14 cm; therefore, it was difficult to exclude the influence of its stimulation on other sites. Future research involving mapping of the motor points of the IL should be performed using an 8-figure coil to investigate the best stimulation site.

Application of magnetic stimulation

Electrical stimulation of the quadriceps femoris muscle was reported to generate larger knee extension torque than magnetic stimulation in patients with a spinal cord injury and complete sensory loss.[13] However, the torque value generated during magnetic stimulation was larger than that generated during electrical stimulation in patients with partial sensory loss or without sensory disturbances.[12, 13] The participants in the present study were healthy and had no sensory problems, and hence, stimulation-induced pain appeared to be a major factor restricting generating torque. The results of this study are consistent with those of previous studies, suggesting that magnetic stimulation is a low-invasive method[21, 22] even if the stimulus intensity is set at the maximum tolerance intensity of the individual subjects.

The advantage of electrical stimulation is that it can simultaneously stimulate plural muscles in the superficial layer, whereas magnetic stimulation can induce deep muscle contraction. In this study, magnetic stimulation of the IL generated larger torque values than electrical stimulation of the 2 hip flexor muscles in the superficial layer together. Our results suggested that the hip joint was one of the most suitable sites for magnetic stimulation as an alternative to electrical stimulation.

With regard to inducing the paralyzed lower extremity ahead during the swing phase, previous studies have reported that hip flexion increases when the action of plantar flexion decreases.[24, 25] During gait training of patients with severe hemiplegia, the ankle joint is usually controlled by ankle-foot orthosis (AFO) or by KAFO. Because of the weight of an orthosis and the compensation of planter flexion torque, the hip flexion torque required in the early swing phase might be greater for patients using an orthosis compared to those not using it. The mean torque value generated in this study was 19.2 ± 8.8 Nm. It may be inadequate to induce the lower extremity ahead because the KAFO weight and the abnormal muscle tone cause difficulty of affected hip flexion at the swing phase. The use of a combined method of electrical stimulation to the SA, TF, and RF, and magnetic stimulation should be considered in the future.

Impairment of patients with hemiplegia is much more severe in distal parts than in proximal parts.[26] Hip and plantar flexion greatly influence an individual's walking speed.[27, 28] The use of electrical and magnetic stimulation to hip flexors in patients with severe hemiplegia is anticipated to strengthen the weak hip flexors or to augment motor control aside from the application during gait training. For the purpose of clinical use, more trials to find the best spot for increasing the hip flexion torque and to decrease pain by moving the stimulation coil on each subject must be needed. Additionally, we should consider the kinematic and kinetic action of the hip flexors during gait and, moreover, investigate subjects and therapeutic protocols of magnetic stimulation in the future.

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FIGURE LEGENDS

Figure 1. Measurement of torque value

The participants first stood on a 10-cm high platform, and the hip joint axis was matched to the machine's dynamometer axis. They were then told to stand half upright on their left leg. The distal part of the right thigh was fixed to the attachment with the right leg raised above the floor.

Figure 2. Stimulus sites on the iliopsoas for placement of magnetic stimulation coils

Point (1) was located at a distance of 2-fingers width lateral to the femoral artery (F. A.) and 1-finger width below the inguinal ligament (Ing. Lig.). Point (2) was located on the line connecting the navel with the anterior superior iliac spine (ASIS), beside the lateral site of the right rectus abdominis muscle. Point

(3) was the midpoint of point (1) and point (3).

Figure 3. Locations of the surface electrodes

The 2 electrodes were placed over individual motor points of 2 separate muscles. The following 3 conditions were selected for electrode placement. Conditions:

(1) The individual motor points of the sartorius and the tensor fasciae latae (SA + TF)

(2) The individual motor points of the sartorius and the rectus femoris (SA + RF)

(3) The individual motor points of the rectus femoris and the tensor fasciae latae (RF + TF)