INTRODUCTION

We recently developed a hybrid exercise system in which electrically-stimulated antagonist muscles are used to resist volitional contractions of the opposing agonists. (Figure 1) This system has already been used successfully to strengthen the lower extremities of healthy men. (Yanagi, et al., 2003) This pilot study explores the feasibility of extending this concept to the training of motor function.

Reciprocal limb movements are central to walking and many activities of daily living. Despite their importance, training is usually relatively primitive and typically involves multiple repetitions of the desired activity. This approach permits training of the desired pattern of movements but does not lend itself to increasing the subject’s strength much above that needed for the task. Our goal was to combine hybrid exercise and ergometer training and study its potential in strengthening muscle in a functional reciprocal pattern that matches that of daily life.

Effects of electrical stimulation on ergometer leg cycle motion may be studied in three ways. The first is to compare the electromyographic (EMG) activities that occur as the subject pedals the ergometer with and without electrical stimulation. The second is the comparison the joint torques produced with or without the stimulation. The third is to examine stimulation-assisted leg motions and reaction forces acting at the pedals.

METHODS

Recumbent Ergometer Leg Cycle Motion

Recumbent ergometers have the advantages of being inappropriate for subjects that have mobility impairments that prevent effective walking or safe sitting balance. This makes them ideal for use in a rehabilitation environment. We developed a recumbent ergometer for this study that is equipped with an electromagnetic brake for resisting crank motion independent of angular velocities of the crank. The encoder measures the crank angle. The potentiometer measures the pedal angle and the strain gauge the forces acting in the plane motion (Figures 2 and 3).

Figure 1: Hybrid exercise of the knee flexors.

Figure 2: Recumbent ergometer.

The ergometer permits training of leg cycle motions that are characterized by a reciprocal motion. The reciprocal nature of ergometer training has advantages in rehabilitation of reciprocal activities such as walking. The motion consists of extensions and flexions of hip, knee and ankle joints. In this study, movements of right leg joint are measured. The angular motions of each joint are measured with a CCD camera with a sampling rate of 20 Hz. The pedal and crank angles and the reaction forces are sampled at 1kHz. These measured data are used to calculate joint torques.

Figure 3: Definition of crank angle.

Electrical Stimulation Assistance

Electrical stimulation device. The electrical stimulation device used in this study (Yanagi, et al., 2003) can generate a bipolar voltage of adjustable amplitude. Pulse widths...
intervals are also variable but in this experiment were set at 2.4 msec and 50 msec (Figure 4).

**Stimulation patterns.** Stimulation patterns in this study were modeled as trapezoidal waves on the basis of EMG activity observed in the rectus femoris and hamstrings during pilot studies of ergometer motion (Figures 5A and 5B). The EMG activity burst of rectus femoris occurring at 1.6 sec in Figure 5A was ignored for the sake of simplicity. The periods of the stimulation are defined as percentages of one cycle. The cycle time starts at every crank angle 0°.

**Evaluation**

Three methods were used to evaluate assisted motions by electrical stimulation: EMG with electrical stimulation, joint torque, and assisted leg motion.

**EMG with electrical stimulation.** Voluntary EMG activities with or without electrical stimulation during ergometer pedalling were compared to examine the effects of stimulation.

Figure 6 shows the EMG recording of the subject’s vastus lateralis as he performed a flexion-extension cycle of stimulation while his vastus lateralis and rectus femoris were stimulated at an intensity of 20 V. The intervals (a) and (b) reveal transient spike responses to stimulation of < 30 msec that include M, H, and F waves. The EMG activity of the volitional contraction is obvious once the transients have passed. The voluntary EMG activity following stimulation can be seen during the interval (c) of 15 msec.

The mean value between 15msec from the end of (b) of Figure 6 is calculated by using the following expression, the Average Rectified Value (ARV) :

$$ ARV(t) = \frac{1}{T} \int_{t}^{t+T} |e(\tau)| d\tau $$

where:
- $T$: period of interval (c)
- $e$: EMG

**Figure 6: EMG with electrical stimulation.**

We use a custom developed electromyographic machine. This device is a low noise type electromyograph which can be easily attached and removed from the skin. It is designed to include active electrodes that are not affected by skin impedance. The EMG activities were measured at 5 KHz sampling frequency and passed through a 5-1,000 Hz band-pass filter. Figure 7 shows electrical circuits of our developed electromyograph.

**Figure 7: Low noise type electromyograph.**
**Joint torque.** Cycle motion occurs in two-dimensional plane. Joint torques are estimated by a planar leg model which consists of three rigid links representing the thigh, shank, and foot which are joined by frictionless pins. The foot is fixed to the pedal (Figure 8).

Dynamic equations are as follows:

\[
\begin{align*}
\tau_a &= J_a \dot{\theta}_a \\
- n_s (x_p - x_s) - f_p (y_p - y_s) \\
- n_s (x_s - x_a) - f_s (y_s - y_a) \\
\tau_k &= \tau_k + J_k \dot{\theta}_k \\
- n_s (x_s - x_k) - f_s (y_s - y_k) \\
\tau_f &= \tau_f + n_s \dot{\theta}_s \\
- n_s (x_k - x_f) - f_s (y_k - y_f) \\
\end{align*}
\]

(2)

\[
\begin{align*}
f_a &= f_p - m \ddot{x}_a \\
n_a &= n_p - m \ddot{y}_a + g \\
f_k &= f_a - m \ddot{x}_k \\
n_k &= n_a - m \ddot{y}_k + g \\
n_f &= n_k - m \ddot{y}_f + g \\
\theta_j &= \text{joint torque [Nm]} \\
J &= \text{moment of inertia [kgm}^2\text{]} \\
\theta &= \text{joint angle [deg]} \\
f &= \text{horizontal force [N]} \\
n &= \text{normal force [N]} \\
m &= \text{mass [kg]}
\end{align*}
\]

(3)

Assisted leg motion. Figure 8 shows that we can recognize easily how the motion of leg and the force are changed by electrical stimulation.

**RESULTS AND DISCUSSION**

This study was approved by our Ethics Committee. The subject was an able-bodied 24-y/o man.

**Stimulation Intensities**

Three conditions were studied: cycle motion at π rad/sec without the electrical stimulation, Case-1; cycle motion π rad/sec assisted by stimulation, Case-2; no motion with during stimulation, Case-3. The EMG activity was sampled in the subject’s rectus femoris and hamstrings at 5 kHz. In Cases 1 and 2, reaction forces were observed and sampled at 1 kHz under a load of 2.5Nm produced by the electric brake.

The stimulation intensities were established as follows: lower bases of trapezoidal waves were set as threshold voltages; upper bases were set as an average of tolerable-maximum and threshold voltages. The recording data was averaged. The three cases are summarized as Table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>rectus femoris</th>
<th>hamstring</th>
<th>leg cycle motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>0 V</td>
<td>0 V</td>
<td>○ π rad/sec</td>
</tr>
<tr>
<td>(2)</td>
<td>32.03 V</td>
<td>25.94 V</td>
<td>○ π rad/sec</td>
</tr>
<tr>
<td>(3)</td>
<td>32.04 V</td>
<td>25.95 V</td>
<td>× 0 rad/sec</td>
</tr>
</tbody>
</table>

**EMG with Electrical Stimulation**

Figure 9 shows a comparison the ARV of rectus femoris in each experiment. The amplified EMG signals are displayed directly in this figure.

A comparison of Case 1 and 2 indicates that voluntary EMG activity decreases when electrical stimulation occurs. In the Case-2, muscles are contracted voluntarily and electrically. The difference of the ARV of two cases shows the effects of the stimulation.

Case-3 shows that the EMG of interval (c) in Figure 6, after 30 msec of the electrical stimulation, does not include voluntary muscle activity. In all experiments, the data of 0.15V or less was unreliable due to the small (< 15μV) amplitude of raw data. It should be noted that the ARV depends on resolutions of the electromyograph.

**Figure 8:** Cycle motion model and main symbols.

**Figure 9:** ARV of rectus femoris in one leg cycle.
**Joint Torque**

Figure 10 shows joint torques; the figure (A) represents the case without the stimulation; and the figure (B) represents with the stimulation situation. These figures highlight the following two points: First, maximum values of torques about the knee and hip joints that occur during stimulation are larger than those that occur without the stimulation; Second, joint torque with the stimulation changes gradually.

![Joint Torque Graph](image)

**Figure 10**: Joint torques.

**Assisted Leg Motion**

Figure 11 shows the limb motion and the reaction forces that occur with and without stimulation. While knee motion was produced as desired, stimulation overflow effects also induced ankle movements. This shows that stimulation intensities need to be carefully chosen and are an area for future investigation.

![Leg Motion Diagram](image)

**Figure 11**: Leg cycle motions and reaction forces.

**SUMMARY**

Motor function training with a combination of hybrid exercise and an ergometer appears feasible. However, more research on refining stimulation patterns and techniques is necessary before its clinical potential role can be established.

**REFERENCES**