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Basic study on a walking assist system with electrical stimulation for elderly people

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Abstract—**The purpose of this study is to examine the usefulness of a walking assist system using electrical stimulation. Thirty-two elderly people (18 men and 14 women) having no medical problems and five healthy young men participated in the study. The electrical stimulation was carried out in two cases: 1) hybrid training (HYBT) for the elderly subjects, 2) assisted walking aimed at eventual application in elderly individuals. The intensity of the electrical stimulation is 80 % in case 1) and three patterns of 60 %, 70 %, and 80 % of the measured maximum tolerable voltage (mMTV) in case 2). The HYBT effectiveness was the same or greater than that of weight machine training (WMT), and could improve the motor function of the lower limbs. During the assisted walking, the peak value of the vertical acceleration of the third lumber vertebra increased in contrast with the non-assisted walking. Steps and changes in the peak acceleration values in the sagittal plane also showed a tendency to increase due to the electrical stimulation. These results suggest that electrical stimulation can contribute to restore the weakened physical function of elderly individuals. The restoration will reduce the risk of falls and increase the daily activities.**

I. Introduction

Physical ability decreases with aging and it is difficult for elderly individuals to walk smoothly. This leads to an increase in the risk of falls and decreases the activities of daily living and quality of life (QOL). In recent years, functional electrical stimulation (FES) has received much attention and has been put into practical use [1,2,3] for restoring physical ability. We are researching and developing methods to improve the gait of elderly individuals by use of an applied FES system. We deal with two systems in the present study: 1) hybrid training (HYBT) of the lower limbs via knee flexion/extension during sitting on a chair or cycling an ergometer, and 2) a walking assist system using a neural network that learns the walking state using signals from small wireless motion sensors attached to the body. The purpose of this study is to verify the advantage of these systems quantitatively. As the acceleration of the third lumbar vertebra is equivalent to that of the center of the gravity [4,5], the acceleration of that vertebra via a wireless sensor is used as an evaluation index.

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II. Hybrid Training

A. Hybrid training method

A recently developed HYBT method [6] that resists the motion of a volitionally contracting agonist muscle with the force generated by electrically stimulated antagonist enhances training efficacy (Fig. 1) and is an alternative to the weight training (WT) methods. Several studies have reported that the HYBT method is effective in increasing the muscle strength and mass in the upper and lower extremities of healthy young men compared with the WT methods and neuromuscular electrical stimulation only [6,7,8]. In addition, the HYBT method contributes to maintain bone mineral density (BMD) because of the simultaneous contraction of agonist and antagonist muscles [9]. Moreover, the HYBT has the advantages of being a compact and light weight training system.

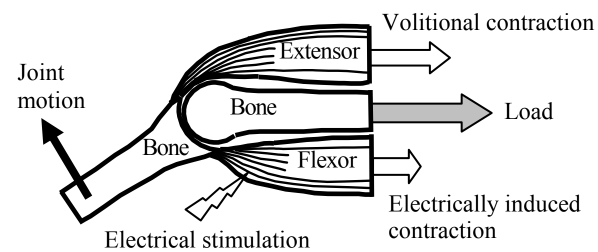


Figure 1.The extension motion of the hybrid training method.

B. HYBT for elderly subjects

Twenty subjects (6 men and 14 women, 60–77 years of age) were randomly divided into two groups: an HYBT group and a WMT group. All subjects performed knee extension and flexion for 19 min, twice a week, for 12 weeks.

All subjects completed the training sessions, with none dropping out and none sustaining any injuries. Knee extension torque increased significantly in both groups (39 % in the HYBT group and 42 % in the WMT group, $P < 0.05$) [10]. The knee flexion torque significantly increased in the HYBT group (17 %, $P < 0.05$), but it did not show a significant change in the WMT group (9 %, $P = 0.167$) [11]. The cross-sectional area of the quadriceps and hamstrings significantly increased in both groups (9 % in the HYBT group and 14 % in the WMT group, $P < 0.05$) [10]. The P values were calculated by the exact Wilcoxon signed rank test of the program package Ver. 9.2 (SAS Institute, USA).

The condition of the iliopsoas muscle is strongly correlated with active walking, maintaining an upright posture, and preventing falls. However, the iliopsoas muscle is a deep muscle, and direct surface electrical stimulation is not applicable to strengthening it. Thus, we adopted the HYBT to strengthen the iliopsoas muscle with stimulating an antagonist gluteus maximus muscle. A motorless and viscous frictionless ergometer was designed for this experiment, and was operated at a pedal speed of 60 rpm.

Two groups of six subjects each were considered to evaluate the effect of the HYBT. Each subject was assigned into the HYBT ergometer group (all men, 68–82 years of age) and the ergometer group (all men, 65–78 years of age). They all exercised for 15 min, twice a week, for 6 weeks. Stimulation intensity in the former was 80 % of the mMTV of each muscle. The pattern of stimulation is shown in Fig. 2. Fig. 3 shows (A) the electrodes attached on the gluteus maximus and hamstring muscles and (B) the ergometric cycling in both groups. The stimulated hamstring during cycling resists the knee extension in order to increase the voluntary effort of contralateral hip flexion.

TABLE I shows the comparison between pre- and post-training in both groups. The P values in the table were obtained by a two-sided test using JMP9 (SAS Institute, USA). A 10-stair up and down, a 10-m walk, and the knee flexion/extension torque showed a significant difference ($P < 0.05$). The hip extension torque also showed a significant tendency of increasing.

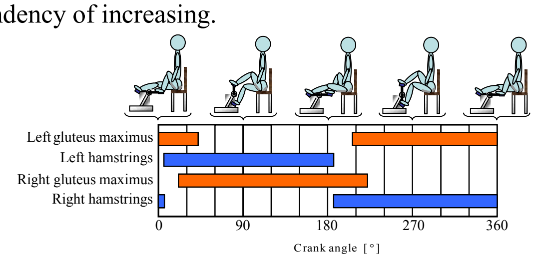
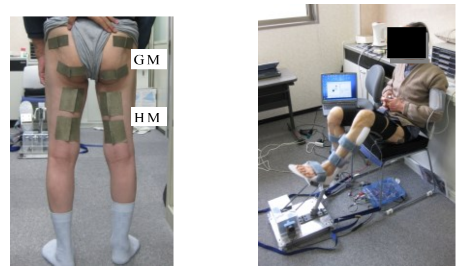


Figure 2. Stimulation patterns during the HYBT ergometer test. The crank angle is set to zero degrees when the left foot is in the furthest horizontal backward position.

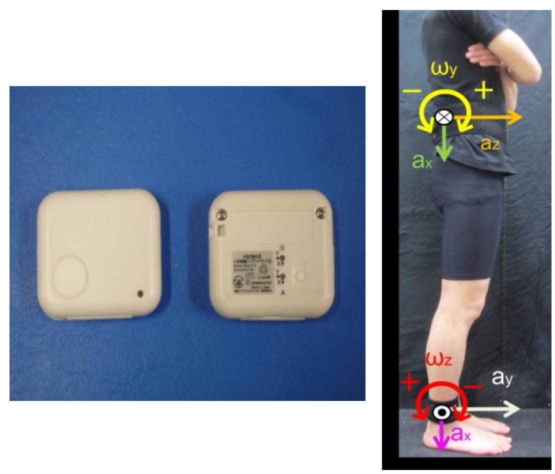


(A) (B)

Figure 3. HYBT using an ergometer. (A) electrode placement, GM: Gluteus maximus, HM: Hamstring muscles (B) cycling motion against electrically induced antagonist resistance force.

III. Walking Assist

A. Motion Senso In this experiment, we used two wireless 9-axis motion sensors (Wireless Technologies WAA-010, Japan, Fig. 4 (A)) with a sampling frequency of 200 Hz and low pass filtering at a cutoff frequency of 100 Hz. The sensors were placed at the location of the third lumbar vertebra and right ankle joint, as shown in Fig. 4.



(A) (B)

Figure 4. Motion sensors. (A) wireless sensor (39 mm × 44 mm × 12 mm and 20 g) , (B) placement.

TABLE I. Comparison of pre- and post-training. The values in torques are normalized by the mass of each subject. P values are in a two-sided test.

Training/test	Hybrid ergometer		*t*	Wilcoxon	Ergometer		*t*	Wilcoxon
Pre- and Post-training	Pre-	Post-	P	P	Pre-	Post-	P	P
10-stair up and down, [s]	7.44±0.84	6.03±1.54	**0.029**	**0.031**	11.19±1.21	9.96±1.68	0.069	0.063
10-m walk, [s]	7.38±0.72	5.80±0.58	**0.010**	**0.031**	7.15±0.84	6.43±0.59	**0.047**	0.063
Hip flexion torque at 60 ° / s , [Nm/kg]	1.24±0.48	1.56±0.49	0.557	0.688	1.53±0.68	1.62±0.77	0.361	0.625
Hip extension torque at 60 ° / s , [Nm/kg]	2.05±0.94	2.36±0.76	0.084	0.063	1.51±0.37	1.64±0.41	0.285	0.406
Knee flexion torque at 60 ° / s , [Nm/kg]	1.11±0.45	1.51±0.48	**0.005**	**0.031**	1.40±0.68	1.65±0.69	**0.041**	0.063
Knee extension torque at 60 ° / s , [Nm/kg]	1.98±0.76	2.50±0.93	**0.021**	**0.031**	2.35±0.83	2.59±0.85	**0.015**	**0.031**

B. Neural Network

Target data for the neural network learning were created from the angular velocity of the right ankle joint sensor. We focused on five notable events in the walking cycle: extracted heel contact, foot flat, heel off, toe off and swing phase.

We then divided them into four sections, as shown in Fig. 5; the first section from point A (heel contact) to point B (foot flat), the second section from point B to point C (heel off), the third section from point C to point D (toe off), and the fourth section from point D to point E (swing phase).

The neural network consists of three layers of 15 input, 23 hidden, and 4 output layers. Data to the input layers of the neural network were as follows: from the ankle joint, an angular velocity around the lateral z-axis, acceleration in the vertical x-axis, acceleration in the anteroposterior y-axis; from the third lumber vertebra, acceleration in the vertical x-axis and acceleration in the anteroposterior z-axis. The current time and one and two previous time of the sampled data were also input.

In a learning stage, typical data were fed into the input layers of MATLAB Neural Network Toolbox as the target data, and neural network weights and biases used in the next recognition stage were obtained. During the recognition, the obtained weights and biases were tested in a simulation in the MALAB/SIMULINK environment. The recognition rate was defined as the percentage of correct answers in each section. These two stages confirm the validity of the proposed neural network.

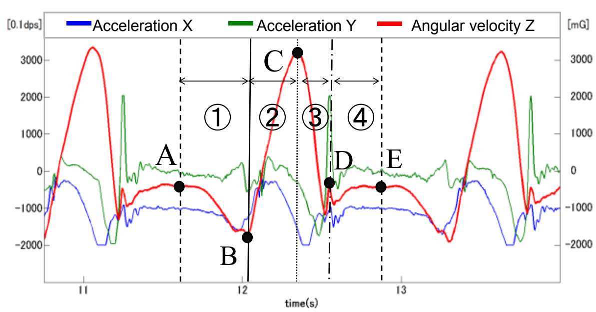


Figure 5. Four sections of the gait cycle.

C. Electrical Stimulation

During the practical use experiments, two four-channel stimulators were used. We attached electrodes to the tibialis anterior and common peroneal nerve (ch1), gastrocnemius (ch2), and soleus muscle (ch3) in each leg. We set the stimulation voltage as three patterns to 60 %, 70 % and 80 % of the mMTV. The stimulation patterns are shown in Fig. 6 and the average stimulation voltages of ch1, ch2, and ch3 were 36 V, 24 V, and 32 V, respectively.

In this study, before applying the system to elderly individuals, we conducted experiments with five healthy young men (21–22 years of age, mean height 170 ± 2.44 cm). Firstly, these subjects walked in order to create the target data from their gait data. Secondly, we performed neural network learning. The walking speed was slow as the subject physical feeling. This is due to the fact that the walking speed of elderly people generally decreases compared with that of young people.

We then measured the gait using the walking assist system. The tibialis anterior muscles, peroneal nerve gastrocnemius muscles, and soleus muscle were stimulated using our surface electrode stimulation device according to the output of the neural network. For the assessment, we compared the system-assisted gait with the non-assisted gait by measuring the accelerations of the third lumbar vertebra and steps. The schematic view of the experimental system is shown in Fig. 7.

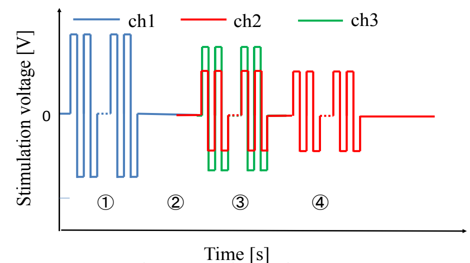


Figure 6. Stimulation patterns.

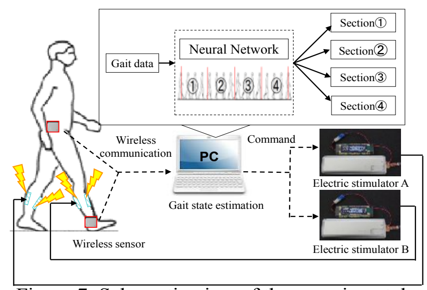


Figure 7. Schematic view of the experimental system.

D. Experimental Results

The mean recognition rate in the assisted gait was 52.3 % in spite of the high rate in the non-assisted gait, 96.7 %. In the non-assisted gait, the steps were 56.0 ± 5.4 cm. In contrast, in case of the assisted gait, the steps were 56.0± 5.8 cm at 60 %, 57.4 ± 6.7 cm at 70 %, and 58.4± 6.5 cm at 80 % of the maximum voltage. The steps at 80 % stimulus increased significantly (P=0.01) comparing that of the non-assisted gait.

TABLEs II and III show the results of acceleration between the assisted and non-assisted gaits. Comparing the acceleration of the lumbar vertebra, in all stimulation voltage patterns used for the walking assist system, the peak value of the acceleration to the upside increased, and a significant difference was observed at the significance level of P = 0.05. For acceleration in the anteroposterior direction, except for one subject, an increase in the peak value to the front was achieved.

IV. Discussion

In this study, we examined the effectiveness of the HYBT on elderly individuals and practical walking assistance by electrical stimulation.

The effectiveness of the HYBT for the lower limbs was the same or greater than that of the WMT, and could improve the motor function of the leg. Ergometer training, whose cycling motion resembles the reciprocal motion of walking, is much safer because it is a sitting exercise, i.e. there is no risk of falling. The safer HYBT using an ergometer was shown to be more effective than the voluntary exercise.

In the electrically assisted walking, the acceleration and step showed tendency to increase as the stimulation intensity was increased. However, when the stimulation voltage was 80 % of the mMTV, some subjects felt discomfort in the case of a long assisted walking. Considering a long time use in the elderly, the adjustment of the intensity of electrical stimulation must be easy and reliable.

From TABLEs II and III, in all subjects, the peak value of the acceleration to the upside increased in the case of assisted gait compared to the non-assisted gait, and in most subjects, the peak value of the acceleration to the front increased in the case of assisted gait compared to the non-assisted gait. The acceleration to the upside is estimated to reach its peak value after toe off [12]. Therefore, the muscle exertion force of the triceps surae was increased by the electrical stimulation. Assist training with additional forces by the stimulation will help strengthen the leg muscles and reduce the risk of falls.

As walking speed increases, the acceleration to the front increases [12]. Therefore, electrical stimulation increases the walking speed. The muscle exertion force in elderly individuals will be increased by using the walking assist system, and their physical ability will be improved. This will, in turn, lead to gait improvement. However, the average recognition rate in the non-assisted gait became worse than that of the assisted gait. This suggests that real-time learning will be required when using the walking assist system.

TABLE II. Peak value of the change in acceleration in the vertical component at the third lumber vertebra. P values are calculated by t-test.

	acceleration in non-assisted [m/s^2]	acceleration in 60% of mMTV [m/s^2]	acceleration in 70% of mMTV [m/s^2]	acceleration in 80% of mMTV [m/s^2]
subject A	3.1	3.3	3.8	3.8
subject B	2.0	2.5	2.5	2.6
subject C	5.6	6.8	7.5	7.6
subject D	2.6	3.4	3.8	3.7
subject E	2.1	2.4	2.8	3.0
mean	3.1	3.7	4.1	4.1
P value		**0.013**	**0.007**	**0.005**

TABLE III. Peak value of the change in acceleration in the anteroposterior component at the third lumber vertebra. P values are calculated by t-test.

	acceleration in non-assisted [m/s^2]	acceleration in 60% of mMTV [m/s^2]	acceleration in 70% of mMTV [m/s^2]	acceleration in 80% of mMTV [m/s^2]
subject A	3.4	2.4	2.9	2.7
subject B	3.1	4.0	4.0	3.9
subject C	2.8	3.4	4.0	3.6
subject D	2.5	3.3	3.3	3.3
subject E	3.1	3.4	3.3	3.4
mean	3.0	3.3	3.4	3.4
P value		0.256	0.126	0.190

V. CONCLUSION

This study contained two trials: the HYBT for elderly individuals to strengthen lower limb function, and the walking assist system for healthy young men by electrical stimulation for eventual application to elderly individuals. It will be necessary to develop a practical and safer HYBT system for elderly individuals and to examine the usefulness of the walking assist system toward improving the gait in elderly individuals. A real-time data processing technique that is both small and light is also required.

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