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Mechanical Power of Ankle Plantar Flexion and Subjective Pain by Monophasic Electrical Stimulation

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Abstract— **The aim of this study was to investigate the mechanical power of the ankle plantar flexion. The investigated power of the ankle plantar flexion would help to improve effectively the FES walking system using the ankle plantar flexion for patients and aged people in slow walking. The subjective pain by electrical stimulation sometimes becomes the burden to use the FES system. We also investigated the relationship between the mechanical power in ankle plantar flexion by electrical stimulation and the subjective pain. We developed the device to measure the ankle movement by electrical stimulation against load resistance torque. The device consisted of pads to support a single lower leg, a rotational footplate with a large pulley and a vertical weight to generate the load resistance torque, and a monophasic electrical stimulator via surface electrodes. Our results showed the proportional relationship between the mechanical power of the ankle plantar flexion and the subjective pain by electrical stimulation. To generate the same level in the ankle plantar flexor power 2.75W under the maximum voluntary exertion, the subjective pain by electrical stimulation exceeded 70, which means the feeling of crying at the Face Pain Scale. This result would help the better design of the FES walking system using the ankle plantar flexion for patients and aged people.**

I. Introduction

THE increased gait variability by slow walking predicts future fall risks. The cases of the slow walking in elderly people [1] and stroke patients [2] are well known. The slow walking is one of causes of side falls is reported [3]. The slow walkers such as elderly people and stroke patients have a possibility of hip fractures caused by side falls, because the fallers in side fall are difficult to support their body by hands. Therefore, the hip crashes to the ground in many side fall cases. The increase of the walking speed in aged people and patients is one of solutions to prevent from the side falls. The walking speed is an important role to keep the stability of walking, because the increase of the kinetic energy in forward movement reduces side movements during walking.

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The ankle plantar flexion by gastrocnemius and soleus muscles is very important to increase walking speed. The weakness of the ankle plantar flexor muscles should be considered as one factor of slow walking in elderly [4] and stroke patients [2, 5]. The simulation results in walking of healthy people show that the ankle plantar flexion by the gastrocnemius and soleus, well contributes to increase forward progression of the trunk [6].

The FES (functional electrical stimulation) walking system for hemiplegia patients focused on preventing the foot-drop by stimulating dorsiflexion muscles in swing period. A recent study to aim at improving the FES walking system delivers to the ankle plantar flexion and dorsiflexion [7]. This study shows that the average contribution of the paretic leg increases 33.1% from 28.8% without FES, but there is no difference between dorsiflexion with plantar flexion and dorsiflexion only, though the ankle plantar flexion is important for walking. However, the increase of the ankle plantar flexor torque by electrical stimulation has great potential to increase the walking speed, from previous studies in walking.

The aim of this study was to investigate the mechanical power of the ankle plantar flexion. The investigated power of the ankle plantar flexion would help to improve effectively the FES walking system using the ankle plantar flexion for patients and aged people in slow walking. In addition, the recent focused hybrid rehabilitation systems consisting of electrical stimulation and mechanical assisting devices have to determine the balance between the power in a joint by electrical stimulation and the power of the mechanical devices.

The subjective pain by electrical stimulation sometimes becomes the burden to use the FES system. We also investigated the relationship between the mechanical power in ankle plantar flexion by electrical stimulation and the subjective pain. This result would help the better design to determine the confortable stimulating condition in the FES walking systems.

II. Methods

A. Experiment device

Figure 1 shows an experimental device to measure ankle movement by electrical stimulation. We developed the device to measure the ankle movement by electrical stimulation against load resistance torque. The device consisted of pads to support a single lower leg, a rotational footplate with a large pulley and a vertical weight to generate the load resistance torque, and a monophasic electrical stimulator via surface electrodes. The device was set on the floor so that the rotational axis of a footplate was vertical against the floor surface. This setup of the device canceled natural rotation of the footplate by gravity. The load resistance torque was generated by the vertical weight *M*[kg] pulling large pulley (Radius *R*=300mm) via wire string with small pulley, which changed the direction of wire string from vertical to horizontal. The large pulley was fixed to the footplate and rotated together, so that the distance from the rotational axis of the footplate to the edge of the large pulley was constant. This means that the load resistance toque was constant on any ankle angles. Therefore, the load resistance torque T_R is solved by a simple equation (1) below.

$$T_R = RMg \tag{1}$$

A subject laid the right side of the subject's body downward on the experiment device. The right leg was firmly supported on the pads of the device. The right foot was fixed to the footplate by rubber bands. The fixing of the subject's foot to the device was carefully carried out so that the rotational axis of the footplate corresponded to the position of the top of the anklebone. The potentiometer, which was set on the rotational axis of the footplate, dynamically detected the angle of subject's ankle movement.

The electrical stimulation to the plantar flexor muscles of the ankle was done via self-glued surface electrodes. The size of the surface electrodes of both anode and cathode was 50mm by 80mm. The cathode electrode was adhered on the top end of the medial and lateral gastrocnemius muscles. The anode electrode was on the bottom end of gastrocnemius muscles. Monophasic rectangular pulse wave by electrical stimulator was employed in this study, because the electrical stimulation with monophasic and rectangular shape is the most effective [8]. The pulse generated by the stimulator was amplified with an isolation amplifier. The recording of ankle angle by the potentiometer was carried out with sampling frequency 100Hz. A trigger at each trial started the recording and the electrical stimulation simultaneously.

B. Procedure

Two load conditions of 0Nm and 5Nm resistance torques were tested. At the 0Nm condition, no weight connected to the wire string. At the 5Nm condition, the initial position of the weight was on the floor at the ankle angle was 0deg. The ankle position 0deg means that the angle between the bottom surface of the foot and the longitudinal axis of the lower leg was 90deg. The length of the wire string pulling the large pulley was adjusted so that the wire string was not slack at the ankle angle 0deg.

The pulse interval D and width W were randomly chosen from D=20ms (50Hz), 33ms (30Hz) and 50ms (20Hz) and from W=0.1ms to 1.3ms by each 0.2ms. The current C of the pulse wave was fixed at 20mA. The subjective pain at each trial was assessed by the Revised Face Pain Scale (FPS-R) [9]. The pain is difficult to measure qualitatively from bio signals, because the nerval system related to pain have not been clear. We used the method on the FPS-R, which is used when doctors ask the level of pain to patients. The Face Pain Scale shows the level numbers with face expressions, for example, the level 0 with a smile face and the level 100 with the face crying and tearing. The subject saw the FPS-R and said the level of the pain at each trial. Each trials started by a trigger, which also started electrical stimulation and recording of dynamic movement of the ankle angle. The stimulation and recording at each trial continued one second, and then the assessment by the FPS-R from hearings was done. Only right leg was tested.

C. Methodology to estimate mechanical power on ankle

To calculate mechanical power of ankle plantar flexion, the torque and angular velocity of the ankle plantar flexion were needed. In this study, we calculate the torque and velocity from the recording of the ankle angle. The torque can be calculated from the equation (2) below.

$$T = MR^2\ddot{\theta} + T_R \tag{2}$$

Here, we assumed that the moment of the footplate and the foot could be neglected, because the moment was very smaller than the moment of MR^2 by the vertical weight. The angular velocity and acceleration were calculated from numerical differential calculus after the noise reduction in recording data by the numerical 1st order low pass filter, which cut off frequency is 5Hz.

The mechanical power was calculated to multiply the torque with angular velocity.

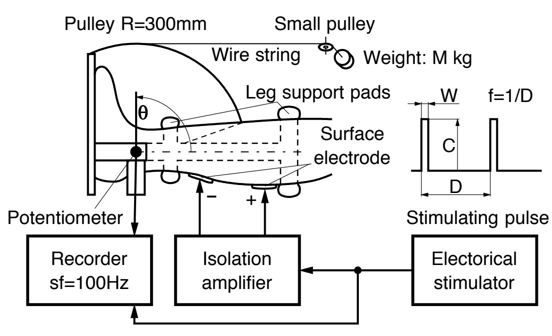

Fig.1 Experimental device

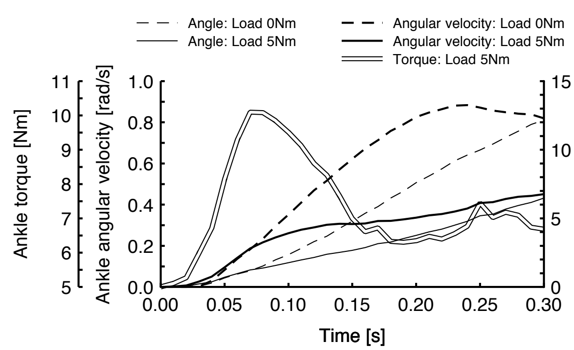

Fig. 2 Time response of ankle movement
D=33ms(30Hz), W=0.9ms, C=20mA

D. Subject

Only one healthy subject in his 20s joined this study. He had no record of nerve diseases in his life. The subject's height was 169cm and weight was 52kg. He had occasional sports activities. The subject was well informed this study and made consents before this study.

III. Results

Figure 2 shows typical ankle movement and estimated ankle torque in the condition of the frequency f=30Hz(D=33ms) and the pulse width W=0.9ms. The time of all data in figure 2 start from the trigger to begin the stimulation and recording simultaneously. The end of time in figure 3 is at the maximum angle of the ankle plantar flexion under the load 5Nm. In the comparison between the load 0Nm and 5Nm, the ankle movements on both cases were similar until 0.75s, however the ankle movement on the load 5Nm became slower than the movement on the load 0Nm as the time passed. The time to reach the maximum angle on the load 0Nm was earlier than the time on the load 5Nm in all f and W conditions. The estimated torque at the load 5Nm rose sharply at the beginning in the ankle movement for acceleration, and then the angular velocity generated and the angle movement began. In this experiment procedure, the ankle did not support the vertical weight at the initial position 0deg, at which the weight was contacted on the ground. Therefore, the estimated torque had 5Nm offset in all times. We focus on three values in the time response with the stimulating frequency f and the pulse width W; 1.Maximum angular velocity, 2.Maximum torque and 3.The time at the maximum torque.

Figure 3 shows the maximum angular velocity by the pulse width W. The increase of W generated faster plantar flexion on both load conditions. The maximum angular velocities on the load 5Nm were slower than the angular velocities on the load 0Nm. The difference in stimulating frequencies to the maximum angular velocity was very smaller than the effect on the pulse width W. The stimulating frequency f in higher conditions generated faster angular velocities. The time at the maximum velocity was about 0.26s(load 0Nm), 0.3s(load 5Nm) in average of the cases W>=0.9ms.

Figure 4 shows the estimated ankle torque by electrical stimulation on the load 5Nm. The maximum torque increased over 10Nm in W>0.9ms. Under the maximum voluntary exertion with the load 5Nm, the maximum ankle torque was 11.5Nm. The increase of W generated larger torque. The maximum torque roughly saturated on W>=0.9ms. The time at the maximum torque were constant around 0.075s on W>0.5ms. We did not found clear differences in stimulating frequencies.

Figure 5 shows subjective pain in the conditions at each trial. The subjective pain 100 means unbearable pain in the subject. The increase of W caused the proportional increases of the subjective pain. In addition, the increase of the stimulating frequency and the load torque raised the subjective pain proportionally.

Figure 6 shows the mechanical power calculated by the maximum torque and the angular velocity. For the calculation, we used the angular velocities at the time when the maximum torque was exerted, because the initial mechanical power with the maximum torque is very important to design the assisting systems with electrical stimulation. The plots of the mechanical power are set against the subjective pain by figure 5. The mechanical power proportionally increased with the increase of the subjective pain in the cases in any stimulating frequencies. The mechanical power in f=20Hz was slightly higher than the power in f=30 and 40Hz. Under the maximum voluntary exertion on the load 5Nm, the mechanical torque was 2.75W.

IV. Discussion

We investigated the mechanical power of the ankle

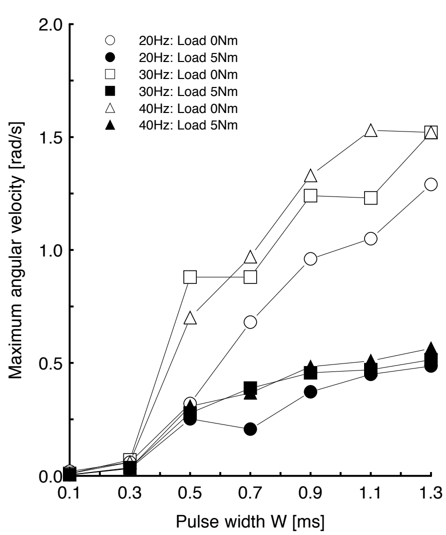

Fig. 3 Maximum angular velocity of ankle movement

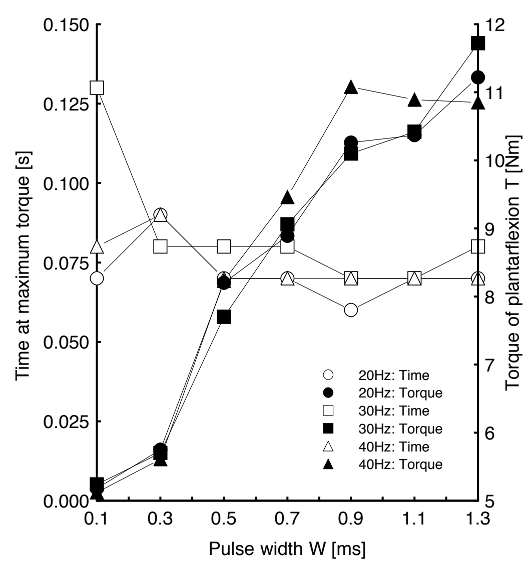

Fig. 4 Torque of plantarflexion

plantar flexion with the subjective pain by monophasic electrical stimulation. For the better design to develop the FES walking s systems with electrical stimulation to use effectively ankle plantar flexion, the confortable stimulating condition with better performance is endorsed. The mechanical power shows the performance to generate torque with velocity against load.

The relationship between the mechanical power and the subjective pain in figure 6 was proportional. Compared with the mechanical power under the maximum voluntary exertion, the almost unbearable situation over 70 in the FPS-R have to be employed if the FES walking system needed the same performance of the maximum voluntary condition. For the design of the FES walking systems to focus on performances, additional mechanical assisting devices would be needed to prevent from the subjective pain.

The muscles of the ankle plantar flexion are very strong to lift the whole body about 60kg at a single leg. For example, the rough estimation of ankle torque in the lifting is 70.6Nm in the case of the horizontal length 120mm from the anklebone to the foot area to support the whole body. From experiences in daily life, human can exert the joint force along with the strength of the load. In this study, only condition of the load 5Nm was tested. We expect the ankle torque increases against the increase of the load resistance.

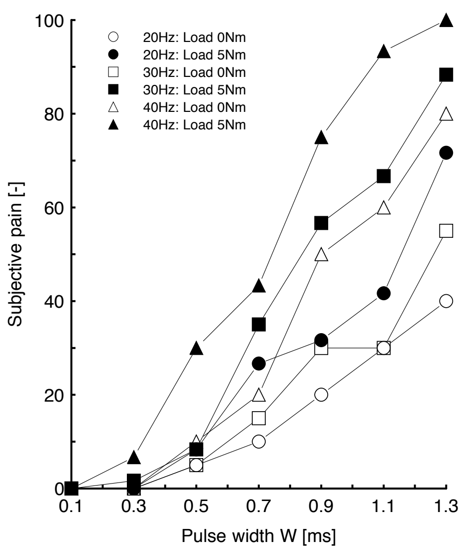

Fig. 5 Subjective pain

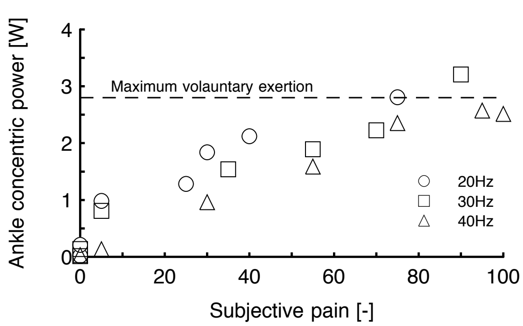

Fig. 6 Ankle power against subjective pain

However, the mechanical power would not increase in proportional to the increase of the load torque. In the case of electric motors, the mechanical power of the electric motors has the point at the maximum power. This is why that the increase of the torque in electric motors means the decrease of the angular velocity. In our case of the ankle plantar flexion, the decrease of angular velocity with the increase of the exerted torque was observed, because the part of the ankle torque is used to pull the vertical weight up. In addition, the Hill's force velocity relationship in muscles [10] gives reasons to this phenomenon.

We found the proportional relationship between the mechanical power of the ankle plantar flexion and the subjective pain, though this study has mainly two limitations: only one subject and two load conditions of 0Nm and 5Nm.

V. Conclusions

We investigated the mechanical power of the ankle plantar flexion and the subjective pain by electrical stimulation. Our results showed the proportional relationship between the mechanical power of the ankle plantar flexion and the subjective pain by electrical stimulation. To generate the same level in the ankle plantar flexor power 2.75W under the maximum voluntary exertion, the subjective pain by electrical stimulation exceeded 70, which means the feeling of crying at the Face Pain Scale. This result would help the better design of the FES walking system using the ankle plantar flexion for patients and aged people.

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