A Left-Right-Asymmetric Pedaling Machine for Medical Rehabilitation of Lower Limbs

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Abstract: This paper explains a pedaling machine of a left-right-asymmetric type for lower-limb rehabilitation. Since most commercially available machines for the rehabilitation of lower limbs are symmetric, people with lower-limb injuries have to adapt themselves to the machines to do exercises. To solve this problem, we have been developing a new kind of pedaling machine that can easily be used to adapt the requirements for left-right asymmetry of lower limbs. Main points in the design of a prototype of a half model for one leg of the machine are summarized. Preliminary tests with a tread force sensor and some electromyogram (EMG) sensors are carried out and are showed the feasibility of the machine.

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1 INTRODUCTION

Maintaining or improving walking ability is essential to ensure a person’s mental and physical soundness. However, many people cannot walk normally due to diseases and/or injuries of lower limbs, brain damage, or aging. Lower-limb rehabilitation is an important way to regain the ability of walking. According to statistics, the number of people in Japan who are issued a certification of needed long-term care or a certification of needed support has been rapidly increasing in the last decade, and the number of people was 5.457 million in 2012 (Ministry of Health, Labour and Welfare, Japan, 2016). As shown in the same report, there will be more than one third of the Japanese to become the elderly in 2035. A large number of people who need rehabilitation will cost large manpower to take care of them. And the increasing number of people who need rehabilitation will become to a serious social problem in the near future. So, developing rehabilitation machines to help people to train their walking muscles not only has a positive influence on people’s physiology and psychology, but also contributes to the whole society.

Nowadays, a great number of rehabilitation machines, which are mainly remodelled from training machines, are often used in rehabilitation. However, those machines have some problems, such as bisymmetric pedaling, fixed structure of machines (for example, Anzai, 2014). Since all those machines are machine-centered, they are hard to meet all kinds of requirements of users for the rehabilitation of lower limbs. They not only may lead to tremendous pain for users, but also may lead to the degradation of motivation for rehabilitation. In order to solve above problems, it is necessary to develop a truly effective machine for rehabilitation.

Riding a bicycle is effective to train walking muscles, but it is not suitable for a user with lower-limb injury. To complete a training task, a user with different degrees of damage in left and right legs subconsciously uses the powerful leg with a great effort. This causes great inadequacy in rehabilitation.

We designed a new type of an asymmetric pedaling machine for lower-limb rehabilitation and built a prototype of a half model for one leg to solve the above mentioned problems (She et al., 2016, 2017a, 2017b). Unlike other ones, it is a human-

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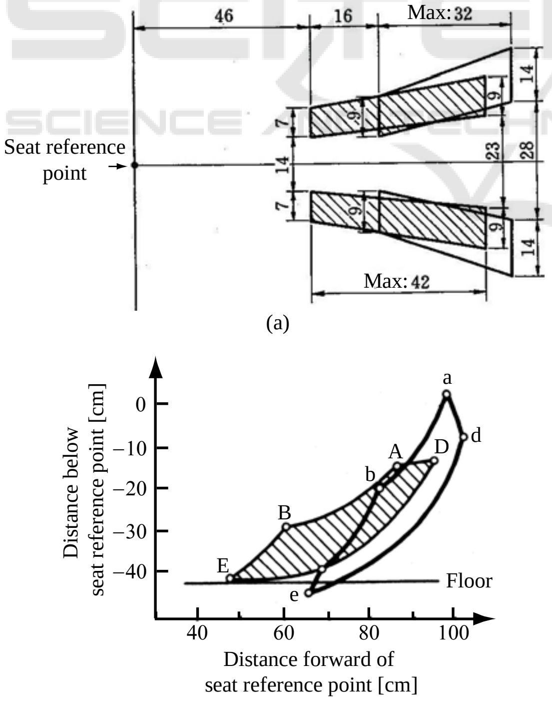
centered machine that the structure of the machine is easy to be adjusted to suit the different requirements for the lower-limb injuries. The left and right pedaling loads and strokes can also be adjusted independently. In order to obtain information about rehabilitation, we built a measuring system to carry out the interaction between exercises and the computer-based supervision (She et al., 2017a).

This paper summarizes the main points in the design of the machine. The results of preliminary tests using a force sensor and some electromyogram (EMG) sensors are presented to show the validity of the pedaling machine for lower-limb rehabilitation.

2 KEY POINTS IN DESIGN OF ASYMMETRIC PEDALING MACHINE

Pedaling is widely used in training the walking muscles. There are basically two kinds of pedaling: rotational and linear. Since a linear type can easily be used to design a left-right-asymmetrical mechanism, we used it to build a new type of a pedaling machine to suit different requirements for lower-limb injuries.



(a)

(b)

Figure 1: Optimal pedaling region. (a) Top view and (b) Side view (Upper case: heel; lower case: toe) (Sato, 1994; She et al., 2017b).

To design a pedaling machine, first, we need to determine the specifications of the mechanism.

As the first step, we selected a pedaling load for a leg-extension force. According to Sato (1994), the maximum of the average leg-extension force of one leg for 20-year-old man is about 2900 N. It decreases with aging from 20s, and the force of people in 60s is only about 50% of that of their 20s. Considering that people who need rehabilitation have very weak legs, we chose the maximum pedaling load to be

$$P_{\max} = 2000\,\mathrm{N}. \tag{1}$$

Then, we determined the range of an adjusting angle for the pedaling machine. There is an optimal pedaling region for a normal person (Figure 1), and the definitions are given in Figure 2. The angle between the femur and the lower leg is in the range [15°, 90°] when the knee is at the closest position to the body, and [30°, 90°] when the knee at the farthest position from the body. Considering that a person who needs rehabilitation may not sit and/or pedal as a normal person does, we chose the angle to be

$$\theta \in [0^\circ, 90^\circ] \tag{2}$$

so that it can provides a larger region than the optimal one does to satisfy the different requirements for users. Based on a preliminary test, we chose the length of stroke of the linear pedaling mechanism to be

$$L = 150\,\mathrm{mm}. \tag{3}$$

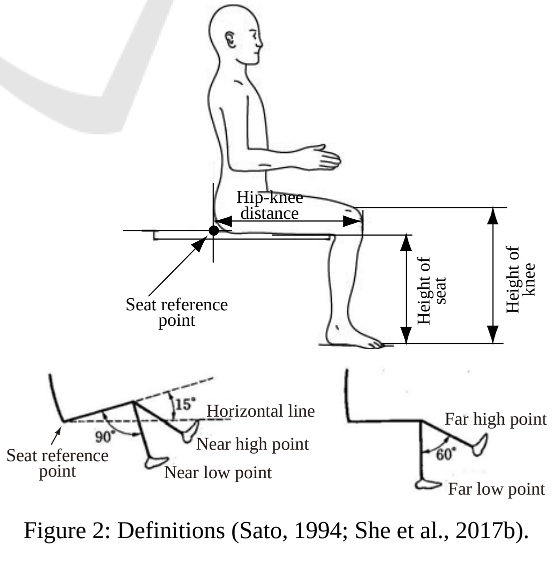


Figure 2: Definitions (Sato, 1994; She et al., 2017b).

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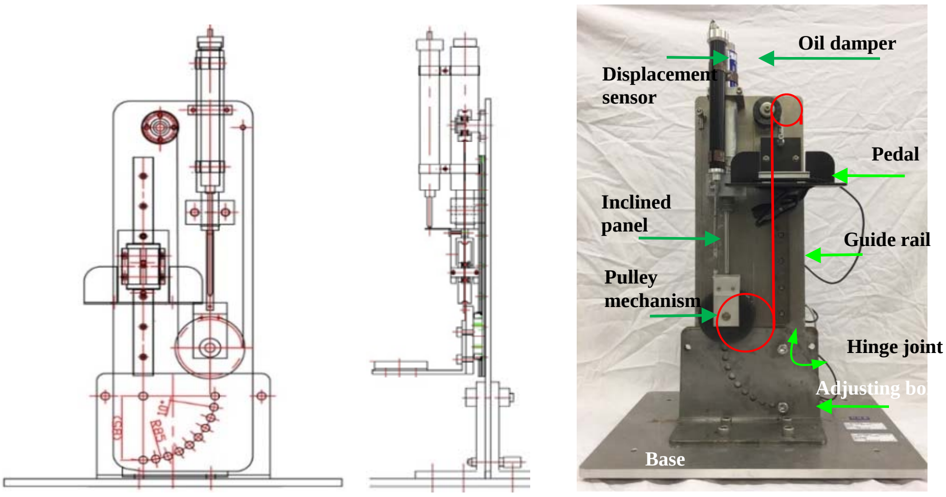

Left lateral view　Frontal view　Photo (right lateral view)

Figure 3: Prototype of pedaling machine for one leg.

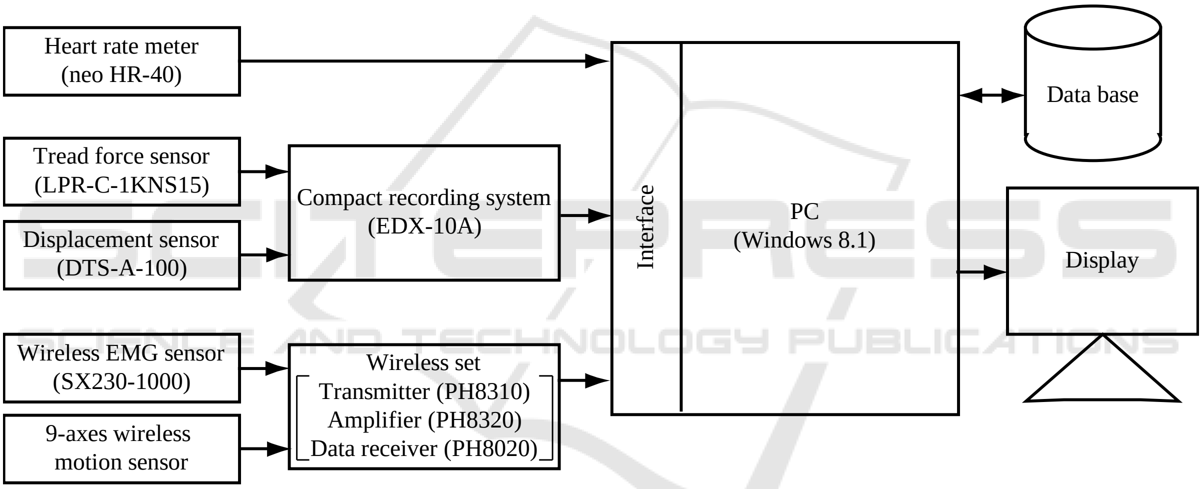

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Figure 4: Measuring system (She et al., 2017).

Table 1: Parameters of oil damper, KINECHECK Super K.

Model	Overall length	Stroke	Force range
5001-31-4	356 mm	102 mm	23 ~ 5440 N

2 PEDALING MACHINE AND MEASURING SYSTEM

We selected components to build a pedaling machine that satisfies (1)-(3).

An oil damper, KINECHECK Super K (Meiyu Aimatic Co. Ltd., Japan) (Table 1), was selected to produce a pedaling load. It has the longest stroke and produces the largest damping force in small-size oil dampers. The maximum force is more than twice of $P_{\max}$ in (1), but the stroke is about half of L in (3). So, we designed a pulley mechanism to enlarge the stroke two times and to reduce the force to half. A prototype of the machine for one leg was built (Figure 3). And an inclined angle of the adjusting part was designed to be changed from 0° to 90° to ensure (2).

As shown in Figure 3, an inclined panel is fixed to the base by two bolts. The angle from 0° to 90° is equally divided by 10°. Resetting and fastening the bolt turn the inclined panel at a desired angle to suit a user's need. The pedal is directly connected to the oil damper by a steel-wire rope in a pulley mechanism. The pedaling force is manually adjusted by turning a nob on the oil damper. The user pushes

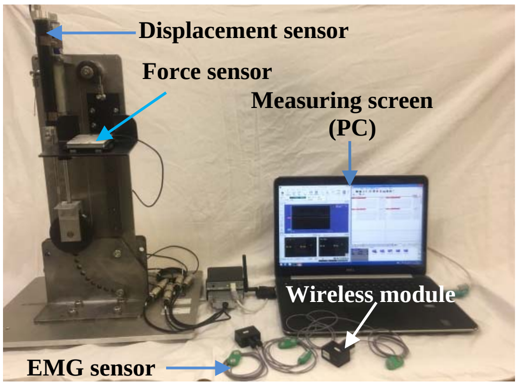


Figure 5: A photo of components of measuring system.

the pedal down in a linear motion for exercise. The pedal returns back to the up position by elasticity produced by the oil damper.

The following points are considered in the design of the measuring system:

- It suitably stores measured data in a real-time fashion.
- It ensures easy access to measured data.
- It displays measured data in a real-time fashion, and easily switches the display to interested data.
- It is easy to synchronize data if needed.

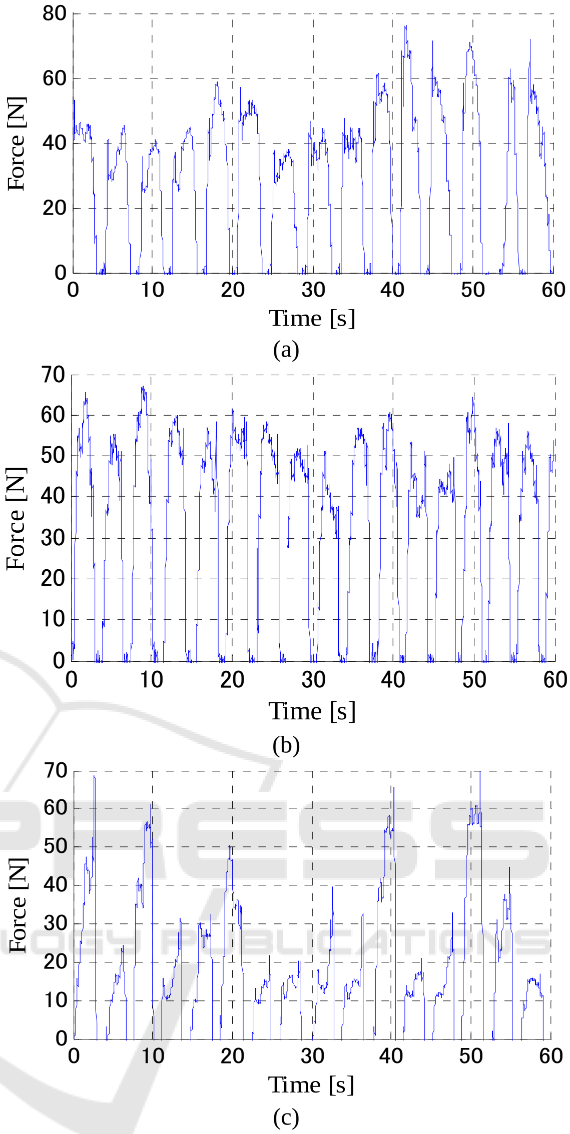
A measuring system (Figures 4 and 5) was constructed to collect data. The measuring system consists of a heart rate meter (neo Hr-40) (NISSEI Co. Ltd., Japan), a force sensor (LPR-C-1KNS15) and a displacement sensor (DTS-A-100) (Kyowa Electronic Instruments Co. Ltd., Japan), one set of wireless EMG sensor (SX230-1000) and one set of 9-axes wireless motion sensor (XYZ geomagnetism, XYZ acceleration, and XYZ angular acceleration) (DKH, Japan).

The measuring system ensures the possibility of interaction between exercises and computer-based supervision and control of medical rehabilitation.

3 PRELIMINARY TESTS

Preliminary tests were carried out for the prototype for three subjects. A subject sat on a fixed chair in front of the prototype machine with a determined distance. The inclined angle was set to be 20°, 50°, and 70°; and the pedaling force was set from 0 to 60 N.

It was found that pedaling was carried out smoothly and comfortably for the inclined angle of 50° among the three setting of 20°, 50°, and 70°.



(a)

(b)

(c)

Figure 6: Pedaling force for different inclined angles [inclined angle: (a) 20º, (b) 50º, and (c) 70º].

Some typical time responses of pedaling force for different inclined angles are shown in Figure 6. As can be seen from the figure, the variation of the pedaling force is the smallest for the inclined angle of 50º among the three angles. This shows that it was the easiest position for the user who pedaled the machine, and it also shows that adjusting the inclined angle of the pedaling machine can easily satisfy the needs of individual requirements.

The muscles of quadriceps femoris, biceps femoris, tibialis anterior, and soleus (Figures 7 and 8) are most closely related to walking. They were measured in preliminary tests. The EMG signals of those muscles were recorded.

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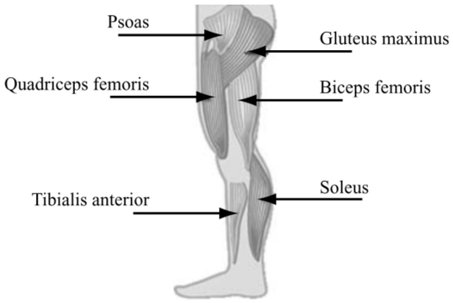

Figure 7: Walking muscles (She et al., 2006).

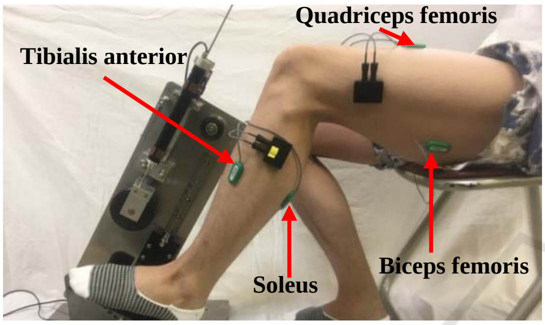

Figure 8: A photo of preliminary test with EMG sensor.

Since the characteristics of the EMG signals can mainly be observed in the frequency range of 50-150 Hz (Marras, 1992; De Luca, 2002), we chose the sampling frequency to be 500 Hz. The FFT (fast Fourier transformation) was used to those signals (Figure 9). The figure shows that the EMG signals were recorded properly.

On the other hand, as pointed out by Carlo J. De Luca (2002), the amplitudes of the EMG signals are stochastic (random) in nature, and can be reasonably represented by a Gaussian distribution function. The usable energy of the signal is in the frequency range of [0, 200] Hz, with the dominant energy in the range of [50, 100] Hz. The usable signals are viewed as those with energy above the electrical noise level. The noise is usually inherent noise in the electronics components in the detection and recording equipment, ambient noise, motion artifacts, and inherent instability of the signal. The amplitude of an ambient noise may be one to three times larger than that of the EMG signals. It is clear from Figure 9 that big amplitudes of spectra at 50 Hz, 100 Hz, and 200 Hz are considered to be the power noise and its harmonics. How to abstract true characteristics of the pedaling motion from the noisy EMG signals is one of the main tasks in this study, and will be investigated in the near future.

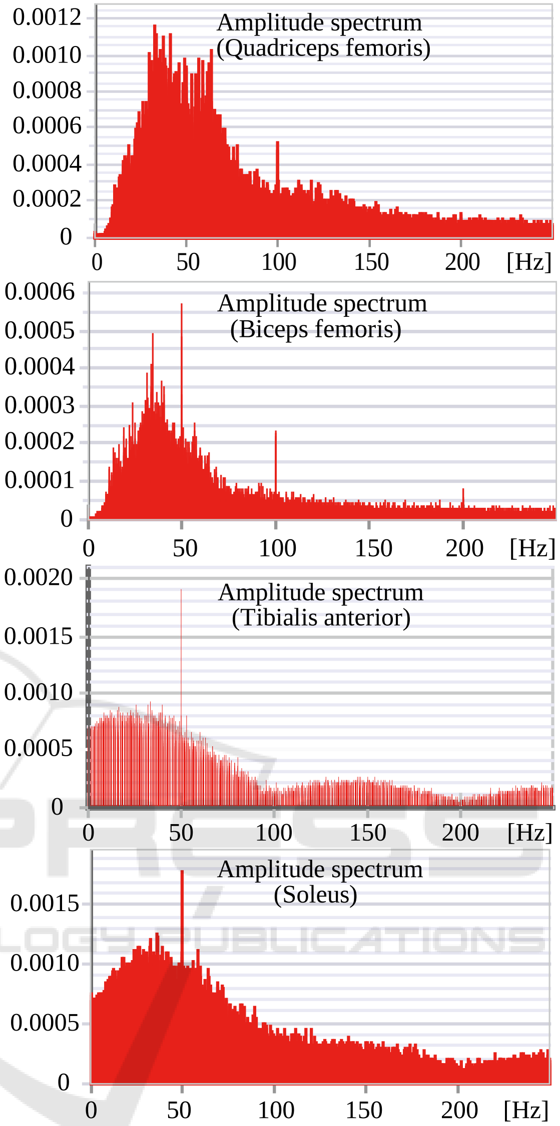

Figure 9: EMG signals of for Load 5 (60 N) and inclined angle of 50º.

4 CONCLUSION

A left-right-asymmetric rehabilitation machine and a measuring system were designed and used in this study. Some preliminary tests showed that this machine was suitable for people carrying out exercise for their walking muscles, and was able to answer the needs for people with lower-limb asymmetry.

On the other hand, preliminary tests also showed that, while the stroke was long enough for exercise, the maximum pedaling load (1) was too large. Experiments showed that setting the maximum

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pedaling load to be 200 N would be large enough for rehabilitation. The part of load generation is planned to be rebuilt in the near future.

To further verify the practicability of the asymmetric pealing machine, we plan to test various normal subjects for the comparison of individual differences (males and females). Then we will analysis the collected data and try to find a way to carry out the control of medical rehabilitation. The performance indexes used in (Smak et al., 1999; Carpes et al., 2010) will be integrated to evaluate the left-right-asymmetry and the effectiveness of pedaling for rehabilitation.

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