

# Development of A Walking Training System for Lower Limb Amputees

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## Abstract

*In recent years, the number of the people affected with life-style related diseases such as diabetes and hypertension is increased. The number of the amputations of the lower limb caused by such life-style related diseases is increased as compared with the external wound such as the traffic and labor disasters. In this research, we develop a prosthetic walking training system for lower extremity amputees that can be utilized from just after the amputation surgery based on virtual reality technology. This system can realize the walking rehabilitation even before completion of the temporary prosthesis.*

*In this paper, structure of the developed system will be explained at first. Secondly, the experimental results of system evaluation by a subject with skillful prosthetic walking will be explained. Finally, application of the developed system to a patient just after a lower limb amputation will be described. The amputee can walk with prosthesis skillfully just after completion of the temporary prosthesis by training with the developed system.*

**Keywords:** lower limb amputees, walking training system, lower extremity prosthesis, virtual reality

## 1 Introduction

In recent years, the number of the people affected with life-style related diseases such as diabetes and hypertension is increased. The number of the amputations of the lower limbs caused by such life-style related diseases is increased as compared with the external wound such as the traffic and labor disasters. Walking training with a lower extremity prosthesis is started after completion of the temporary prostheses and three weeks or more is needed for completion of the temporary prosthesis. Complications are often caused if the amputee spends this term in lying in bed especially for elderly people. Consequently, social reintegration tends to be later since acquisition of the walking ability with the prosthesis gets later. Therefore, it is important to realize walking training with the prosthesis as early as possible after the amputation surgery.

Many researches on walking training system for a person without amputation have been conducted. For example, Tani et al. developed the walking rehabilitation machine with virtual reality technique

using a treadmill[1]. For prosthesis of lower limbs, there are many researches from many points of view. There are many researches on the mechanical aspects of the prosthesis. For examples, Goh et al.[2] evaluate the socket of the prosthesis by means of pressure exerted on stumps. Fridman et al.[3] studied on the influence of alignment of the prosthesis to the gait. Some researches on training method for prosthesis have been conducted recently. For examples, Schon et al.[4] proposed a walking training method with a temporary prosthesis. Chow et al.[5] proposed a prosthetic training method by using auditory biofeedback. Consequently, there is no research on a prosthetic training system that is utilized before having a temporary prosthesis.

In this research, we develop a prosthetic walking training system for lower extremity amputees that can be utilized from just after the amputation surgery. This system can realize the walking rehabilitation even before completion of the temporary prosthesis. Virtual reality technique is employed to realize virtual prosthetic walking environment. In this paper, structure of the developed system will be explained at first. Secondly, the experimental results of system evaluation by a subject with skillful prosthetic walking will be explained. Finally, application of the developed system to a patient just after a lower limb amputation will be described. The amputee can walk with prosthesis skillfully just after completion of the temporary prosthesis by training with the developed system.

## 2 Prosthetic Walking Training System for Lower Limb Amputees

### 2.1 Structure of prosthetic walking training system

In this section, the structure of our developed prosthetic walking training system is described. Fig.1 shows the photo of the developed walking training system. Fig.2 illustrates the system diagram. As shown in Figs.1 and 2, the virtual prosthetic walking training system consists of a virtual prosthetic part, a visual display part, and a computer software part. In the prosthetic part, there exist an intact part and an amputation part. A user stands on the virtual prosthetic part. In the amputation part, there exists a socket for amputated end. The image on the display is changed by stepping on

each part by turns.



Figure 1: Overview of prosthetic walking training system

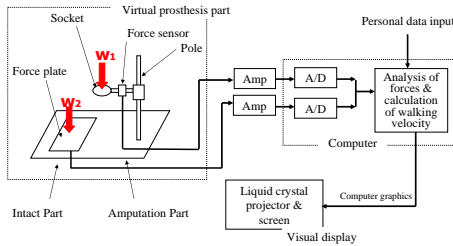


Figure 2: System diagram

As shown in Fig.3, the amputation part of the virtual prosthetic part has the pole and the socket as an interface between the system and the amputated end in order to reduce pain by concentrated load to the end. A user inserts amputated end into the socket. The socket is made by a cast to adapt the differences among individuals and temporal conditions. The pole is fixed to the floor firmly and height of the socket can be changed to adaptive to users' height. There exist force sensors in the intact and amputation parts to measure stepping force. Output values of vertical forces are amplified and inputted to the computer through D/A converters. In the computer software part, inputted vertical forces of the intact and the amputated ends are analyzed and the walking velocity in the virtual environment is determined.

Fig.4 illustrates an example of the displayed graphic images of the walking road. A liquid crystal projector and a screen are utilized to display such images.

## 2.2 Walking rehabilitation using proposed system

In this section, we propose a method to realize prosthetic walking rehabilitation by using the developed system. Fig.5 illustrates the flow of the training. First, a medical doctor diagnoses the individual's condition of the user. Then, the medical doctor determines a threshold of stepping force of the

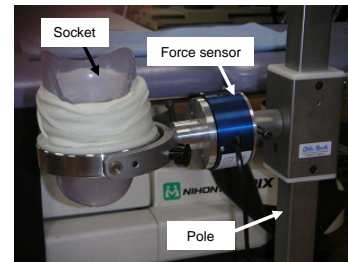


Figure 3: Amputation part

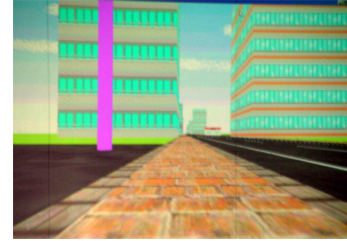


Figure 4: Computer graphics of virtual walking road

amputated end to generate walking. Namely, computer graphics of the walking road are progressed only when the load to the socket exceeds the threshold that is determined corresponding to the individual's condition. At the early stage of the training, small threshold is employed. The threshold is increased gradually corresponding to the recovery of the condition. The detail is explained in the next section.

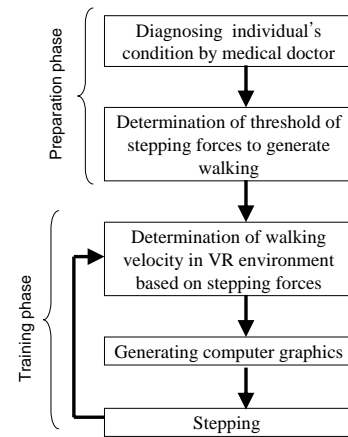


Figure 5: Training procedure

## 2.3 Determination of walking velocity in virtual environment

In this system, walking velocity in the virtual environment is determined by analyzing the vertical forces exerted on the intact and amputated ends. In addition, the velocity can be adjusted to a training phase. Eq.(1) is utilized to determine the velocity.

$$v_i = L/T_{i-1}, \quad (1)$$

where  $L$  denotes the step length of the user, and  $T_i$  denotes the time when the load exceeds the threshold determined by  $w/n$  as shown in Fig.6, where  $w$

denotes a user's weight and  $n$  is arbitrary positive number and subscript  $i$  denotes the values of  $i$ -th step. Namely, quick load yields large velocity. Consequently, the user has to produce the force exceeding the threshold to generate walking velocity.

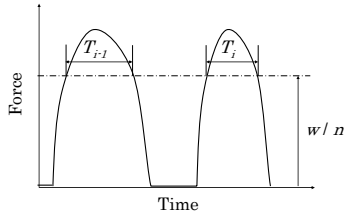


Figure 6: Definition of walking velocity

It is expected that force exerted on the amputated end is not so large due to fear or pain at the beginning of the training. Thus, we set that walking is generated even by a small vertical force at the amputated end. Namely, the variable  $n$  is set to a large value. The threshold is gradually increased corresponding to reduction of pain and the fear, that is,  $n$  is decreased. At the end of the training,  $n = 1$  is set and the whole weight has to be loaded. This function allows us to realize the training adaptive to the individual conditions.

### 3 Evaluation of the system by skillful amputee of prosthetic walking

#### 3.1 Experimental conditions

In this section, we examine whether the system can be applicable to the walking training. A male of 22 years old is employed as a subject. He had a above-knee amputation surgery of his right leg 4 years ago due to a traffic accident. He utilizes prosthesis usually and can run on the flat ground. The weight is 60[kgf] and the threshold of the vertical force is set to 20[kgf] by trial and error. Also, step length in eq.(1) is set to  $L = 0.6$ [m]. In order to investigate differences of force patterns by walking velocities, the subject walked in three velocities. The three velocities of slow, normal, and fast are determined by the subject's subjectivity.

First, the subject inserts the amputated end into the socket. After standing at rest, he starts the stepping foot and amputated end by turns for a minute to generate walking in the virtual environment. During the stepping, the subject gazes the screen.

#### 3.2 Experimental results

The subject mentioned that stepping can be realized without pain on the amputation end. Figs.7-(a), (b), and (c) illustrate the time series patterns of forces of the intact side and the amputated side with slow, normal, and fast velocities, respectively. These figures show that this system can measure the forces smoothly. As shown in these figures, almost similar levels of forces are exerted on the amputated end and intact end.

Fig.8 illustrates the calculated walking velocities by the three stepping velocities. As shown in this figure, walking velocity can be controlled by changing stepping speed.

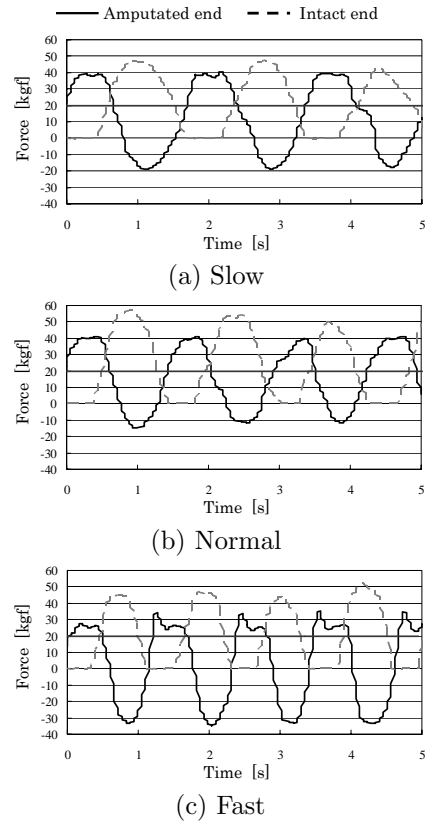


Figure 7: Experimental results of skillful amputee

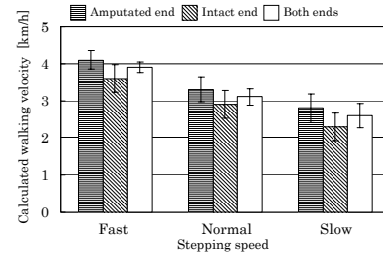


Figure 8: Calculated walking velocities

## 4 Clinical Application

### 4.1 Contents of training

In this section, we apply the proposed system to an amputee just after an amputation surgery. The patient is 22 years old male. He had a above-knee amputation surgery of his right leg September, 2003. The weight is 60[kgf]. The application was done for a month from three weeks after the amputation. In the training, the step length in the virtual environment is set to  $L = 0.6$ [m].

First, the patient inserts the amputation end into the socket. He starts the stepping foot and amputated end by turns for a minute to generate walking in the virtual environment. Handrails are equipped in order to reduce stump pain. The walking velocity is not designated in advance. Namely, the subject determined his walking velocity. The frequency of the training is 5 times per day and around 3 times per week.

## 4.2 Training results

The subject mentioned that he had stump pain for three days from the start, but stepping can be realized gradually without pain on the amputated end.

Fig.9 illustrates the time series patterns of forces of the intact side and the amputated side. Fig.9-(a), (b) and (c) illustrate the results of the first day, two weeks and a month from the beginning, respectively.

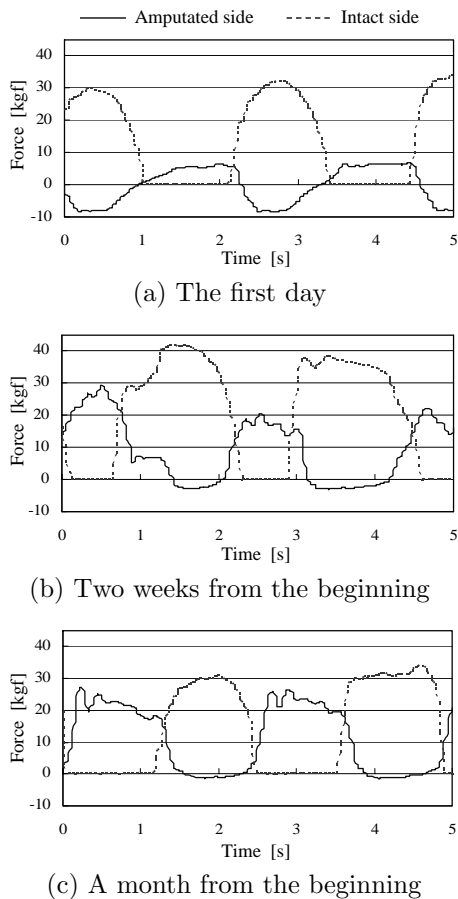


Figure 9: Time series patterns of stepping forces during training

As shown in these figures, he could not load force at the amputated end and loading speed was slow at the beginning of the training. Two week later, he could load much force at the end and loading speed was faster. Finally the force and loading speed reached the same level as that of intact side a month later and incline of the force was increased.

Fig.10 illustrates transition of the maximum forces at the intact and amputated ends. As shown in this figure, maximum forces at the amputated end are gradually increased day by day and finally the force reaches similar level of that at the intact end. And the patient can easily walk with real temporary prosthesis just after its completion. Therefore, we can conclude that the system can apply the prosthetic walking rehabilitation.

## 5 Conclusions

We proposed a new training system for prosthetic walking of lower limb amputee. Experimental

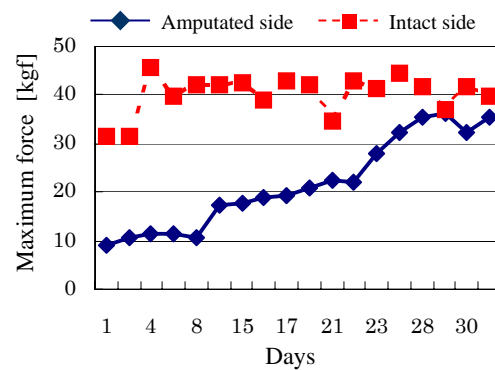


Figure 10: Transition of maximum forces

results with skillful amputee of prosthetic walking have shown that the developed system can measure forces exerted on the intact side and the amputated end and the smooth walking is realized. After that we have applied the system to clinical training of an amputee just after the amputation surgery. By using the system, the force exerted on the amputation end is increased gradually day by day and finally the forces reaches the same level as that at the intact end. And the patient can walk with the real temporary prosthesis just after the training. Consequently, we can conclude that the system can apply clinical training.

As the future work, the system will be applied to many other patients in order to show the effectiveness of the system. Also, we will develop walking mechanism with free natural walking.

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