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Active AFO with Ankle Joint Brake Friction Control using Force Observer

Nobuyuki YOSHIZAWA, *Senior Member, IEEE*

Abstract— **Optimum friction control of the ankle joint brake is essential for realizing a stable gait when wearing an active ankle foot orthosis (AFO). An optimum friction control system using a force observer is designed and simulated. The brake friction is controlled in proportion to the observed human force of the lower limb without using force sensors. The simulated results show that the force observer performs well. The force-controlled orthosis is robust and practical because it uses no force sensors.**

I. INTRODUCTION

Human motion is inherently bilateral, since an action is always accompanied by a reaction. Reaction force measurement is important in the fields of medical haptic forceps control [1], robot control in relation to human-robot interaction [2], as well as power-assisted control [3]. A force observer [1][2][4] based on a disturbance observer has already been successfully adopted as a force measurement tool. The method enables the acceleration of a motor to be controlled without using conventional force sensors. Although there are many kinds of force sensors, they have common problems such as positioning, durability and cost. The force observer is advantageous because it functions without using a force sensor. The force observer has been introduced to observe the human reaction force caused by motor movement, therefore, the system incorporates a motor. However, in principle it may be possible to introduce it into a system without a motor, such as an active ankle foot orthosis (AFO).

An active AFO (AAFO) has been investigated [5]~[9] to improve the activity in patients' daily lives during the conservative treatment period. An active AFO is now being developed to enable a patient to walk comfortably with a fixed ankle without the help of crutches [6]. Previous experimental results revealed the importance of the friction control of an ankle brake [9] in realizing a stable gait. If the friction is large, it causes human fatigue and wastes battery power. On the other hand, small friction leads to an unstable gait. Therefore, optimum control is necessary.

This paper presents an ankle brake control system that employs a force observer. The simulation results indicate the effectiveness of the observer in providing optimum control of the brake based on the observed torque of a lower limb.

II. IMPORTANCE OF FRICTION CONTROL OF AAFO

In this section, I outline the history of active AFOs and present targets for further improvement.

A. Structure

Figure 1 shows a candidate active AFO that I proposed for use with Achilles tendon ruptures [9]. In the figure, the upper part is a conventional AFO. The AFO is supported by a lower stand with a bearing at the ankle. The AFO can swing around the bearing by employing a seesaw mechanism. The bearing is used to allow smooth movement by reducing friction.

An electromagnetic brake (BXW-03012H-12V-8 Miki Pulley Co. Ltd.) is installed at the ankle position. The brake is spring-actuated with a manual release to provide a fail-safe mechanism. A pressure sensor is attached to the sole plate to detect the user's weight. The pressure sensor is a sheet type sensor (FlexiForce) [8]. The electric circuit with a microcomputer and 4 AA batteries is housed in a plastic box attached at the side of the lower stand. The circuit controls the electromagnetic brake.

Figure 1 Side view of AAFO

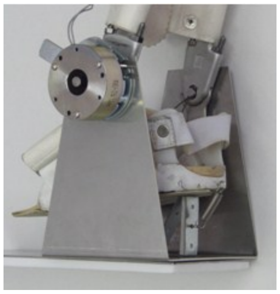

Figure 2 Rear view of AAFO

Figure 2 shows the rear view with the circuit box removed. There is a stopper with a spring fixed to the back of the shoe that mechanically halts the shoe's backward swing. Table 1 shows the active AFO specifications. The total weight of the prototype active AFO is 2.2 kilograms.

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N. Yoshizawa is with the Nippon Institute of Technology, Miyashiro, Minami-Saitama, 345-8501, Japan, (e-mail: yosizawa@nit.ac.jp).

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Table 1 Active AFO Specifications

Stand dimensions	250 mm (L)x170 mm (W)x170 mm(H)
Weight	Circuit + batteries 300 g Steel stand + brake 700 g AAFO total 2.2 kg
Power supply	DC 6V (4 AA batteries)
Brake	BXW-03-12H-12V-8 Miki Pulley Co.,Ltd.
Sensor	FlexiForce

The electric circuit was designed as described below. When a DC current of 150 mA is supplied to the brake, the brake becomes frictionless and the mechanical spring connected to the stopper pulls the shoe. Then the forward inclined AFO Returns to its perpendicular heel strike position. The pressure sensor detects the beginning of the swing phase and, after a delay time, DC current is supplied to the electromagnetic brake. The time delay is needed to prevent the front edge of the sole plate from being dragged across the floor.

B. Gait Trial Results

Figure 3 shows the gait trial results. An able man had the prototype active AFO attached to his right leg, and he then walked on a treadmill. His gait speed was 0.8 km per hour. The brake conditions of the ankle joint of the active AFO were set with three patterns. Pattern A; The brake was controlled according to the gait cycle. Pattern B; The brake was off during the gait cycle. Pattern C; The brake was on during the gait cycle. The numbers in the figure indicate the stages of the gait cycle. One shows the heel strike and five shows the toe off. Figures A1 to A8 show that the patient can walk without the help of crutches or a stick by using the active AFO with the ankle joint fixed at a dorsiflexion angle of 22 degrees. Figure A1' is an enlargement of part of fig. A1 and shows that the sole plate touches down parallel to the floor at the heel strike. On the other hand, when the brake is not controlled, for example in fig. B6, the front edge of the sole plate drags across the floor during the swing phase. Also, in fig. C1, the sole plate touches down at the heel and causes a slight shock to the patient. The experiments revealed that the brake control is essential. In pattern A, the brake was simply on-off controlled. The next section describes advanced brake control.

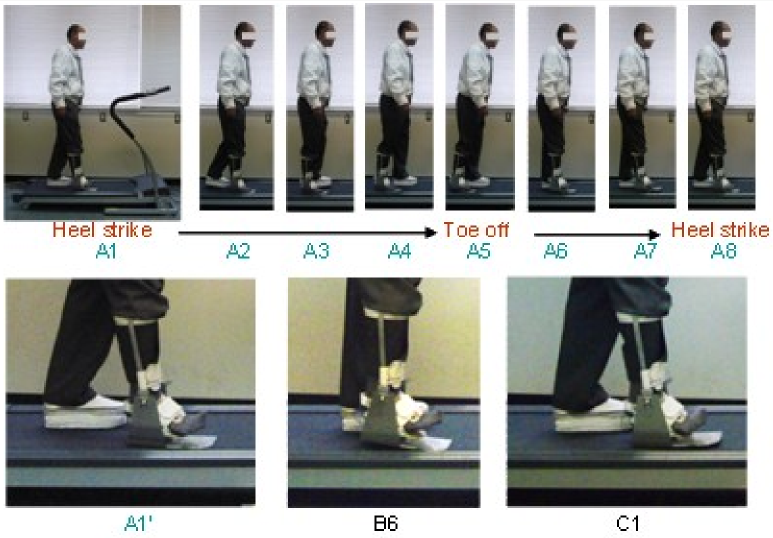

Figure 3 Gait trial results

III. OPTIMUM FRICTION CONTROL

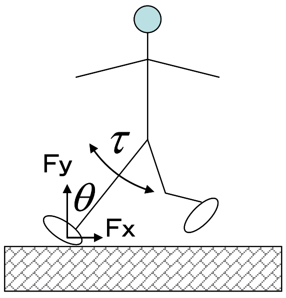

Figure 4 Forces acting on foot.

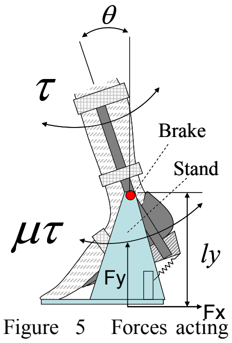

Figure 5 Forces acting on AAFO.

A. Optimum friction control using force observer

Figure 4 shows the forces acting on a foot assuming that there is only one foot in contact with the ground at a time. To realize a stable gait, the horizontal force Fx must be less than the limiting friction for the ground. The leg rotates about the hip joint and torque τ accelerates it forwards. The Fx varies as a function of leg angle θ and is in balance with τ. Figure 5 shows the forces acting on the AAFO where μ is the coefficient of friction of the ankle brake. The torque $\mu\tau$ is given by the resultant moment.

$$\mu\tau = -\mathrm{F}y\,lx + \mathrm{F}x\,ly \tag{1}$$

where lx and ly are the perpendicular distance of the line of action, respectively. Also, θ is given by

$$\tan\theta = \mathrm{Fy}/\mathrm{Fx} \tag{2}$$

The vertical force is equal to the human weight mg where m is the mass of a body and g is gravitational acceleration. Therefore, the torque $\mu\tau$ is approximately given by

$$\mu\tau \cong mg\left(\frac{ly}{\tan\theta} - lx\right) \tag{3}$$

Accordingly, the optimum coefficient of friction of the ankle brake μ is determined by θ and τ. The leg torque τ can be measured by a force sensor or a torque sensor. However, any sensor has both inherent and common problems. Without using force sensors, τ is given by a reaction force observer [1][2][4].

Figure 6 shows a block diagram of the control system where J is the inertia of the plant, namely the AFO, s is the Laplace operator, g_r is the bandwidth of the reaction force observer, G is the gain of the electromagnetic brake, and K is the torque constant. The area enclosed by the dashed line shows the reaction force observer. θ is the rotation angle around the ankle shaft, which is measured by an encoder, and $\dot{\theta}$ is the angular velocity. τ is the torque of the human force applied around the ankle shaft during walking. $\tilde{\tau}$ is the output of the reaction force observer. In the previous section, a pressure sensor was necessary to determine the beginning of the gait cycle. In this system, the pressure sensor is unnecessary because the measured rotation angle θ determines the beginning of the gait cycle.

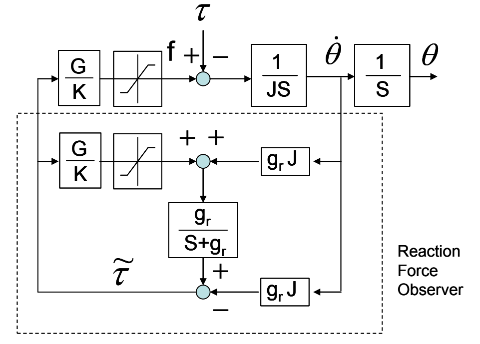

Figure 6 Block diagram of control system.

B. Simulation

The observer output $\tilde{\tau}$ was simulated to estimate the performance of the control system. The human torque τ of a lower limb during walking was simply assumed to be a sine wave of 1 [Nm] magnitude and 1[sec] period. The waveform is shown in fig. 7. Also, simulation parameters J, g_r, G/k were assumed to be 0.2[kgm^2], 20[rad/s], and 1, respectively.

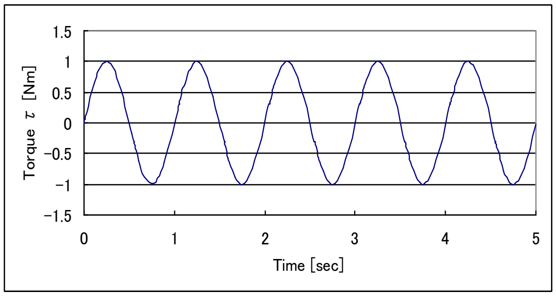

Figure 7 Input of assumed human torque τ

Figure 8 shows the time dependence of the resultant force f+τ. The shape of the resultant force is complicated and changes periodically because the friction of the electromagnetic brake is composed of static and viscous friction. By integrating the resultant force, the angular velocity $\dot{\theta}$ is derived and shown in fig. 9.

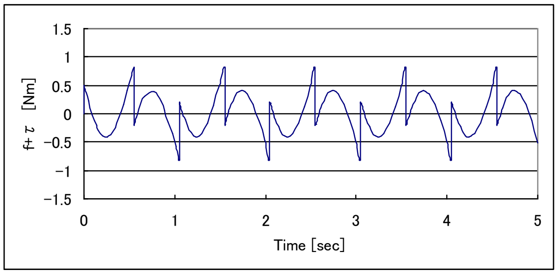

Figure 8 Time change of resultant force f+τ

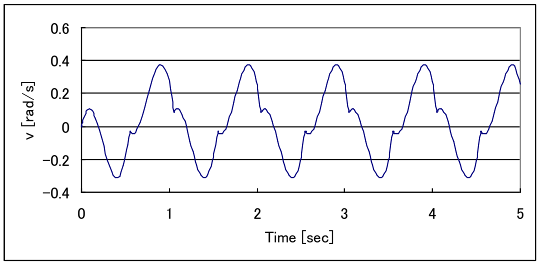

Figure 9 Time change of angular velocity $\dot{\theta}$.

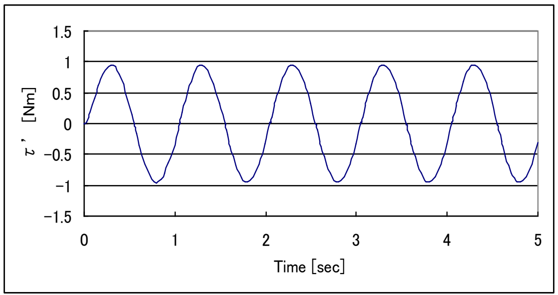

Figure 10 Time change of observed human torque $\tilde{\tau}$

Figure 10 was derived when the signal was submitted to the reaction force observer, and shows the observed human torque $\tilde{\tau}$. The magnitude is 1 [Nm] and the period is 1 [sec], which is identical to the input sine wave torque τ shown in fig. 7. The phase delay is negligible. The simulation result shows that the force observer is very precise and optimum friction control is possible if the electromagnetic brake power is controlled by the observer output $\tilde{\tau}$.

Figure 11 shows the brake force f= $\mu\tilde{\tau}$ when the electromagnetic brake force is controlled in proportion to $\tilde{\tau}$. In the calculation, the offset of the static friction and the viscous friction gain are assumed to be ±0.5 [Nm] and 0.1, respectively. These constants may change due to physical conditions such as brake material, temperature, humidity, and abrasiveness. The constants must be determined experimentally.

This paper used a simulation to examine the possibility of applying a force observer to an active AFO. The system is different from ordinary powered systems because it has no motor. The force observer is expected to have many merits based on the reported success of ordinary powered systems [1][2][4]. However, the advantages and disadvantages of applying a force observer to an active AFO control must be examined and proved experimentally in a succeeding study.

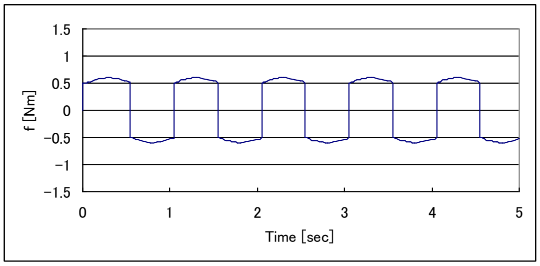

Figure 11 Time change of brake force f.

IV. CONCLUSION

It is important to control the ankle joint friction of an active AFO. A system using a force observer is proposed. The force observer is a practical method of estimating human force and optimally controlling the ankle joint friction of an active AFO. The system is basically robust because it uses an encoder instead of fragile and noisy force sensors.

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