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Automatic actuator control by leg load signal of active AFO for Achilles tendon ruptures

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Abstract— **This paper describes automatic actuator control hardware for an active ankle foot orthosis (AAFO) for a ruptured Achilles tendon. The sole of the AAFO is equipped with a servomotor. The actuator can switch the upright and the forward stepping posture of the patient.**

To control the actuator automatically during a gate cycle, 1: joint kinematics were analyzed that consisted of both stick pictures and EMG signals from the affected limb when the patient was walking on a treadmill. The cross-correlation coefficient between the ankle angle and the EMG signal of the lower limb (tibialis anterior) was small when the patient was wearing the AAFO. 2: An air pressure sensor and a film sensor were compared experimentally to measure the leg load. A prototype AAFO with automatic control was realized by using the leg load signal provided by an air pressure sensor to realize actuator control.

I. INTRODUCTION

RECENTLY, many active actuator mechanisms have been proposed for ankle-foot orthosis [3] （AFO） and knee orthosis [4]. Some are designed for rehabilitation purposes [5][6] and others for treatment [7]. Also, power assisted suits [8] and electric prosthetic limbs have been examined that use electromyographic (EMG) signals for control . The actuator and control mechanisms are very important as regards developing a practical active orthosis. Moreover, a portable active AFO must be light [2] and mechanically reliable.

Last year I proposed the basic structure of an active AFO (AAFO) for the treatment of a ruptured Achilles tendon [1]. The aim was to support the activities of daily living (ADL) during the conservative treatment period [9]. An AAFO is now being developed to enable a patient to walk comfortably with a fixed ankle, and with his weight on the injured leg as soon as possible. The patient can hold the handrail when ascending and descending stairs because his hands are free. The action is safe because the patient can support his weight on his own feet. The AAFO is very useful for assisting with ADL. Later I reported gait trial results for version 2 of the AAFO with an improved actuator mechanism [10]. The gait trial revealed the joint kinematics and stick pictures at a walking speed of 1 km per hour. In prototype 2, a servomotor is employed because it is a simple, lightweight and low power device, and positional control is easy and precise. In these studies, the actuator of the AAFO is controlled manually with a hand switch.

In this paper, I discuss how to control the AAFO automatically and report experimental results. EMG signals and leg load signals are compared in terms of their potential for use as control signals.

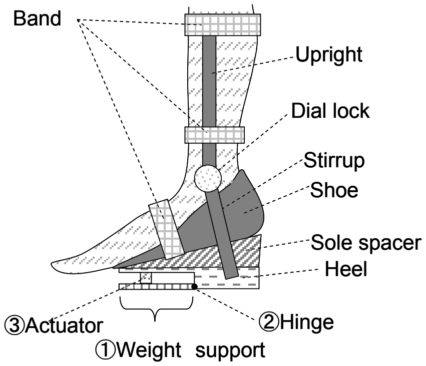

Fig.1 Basic structure of AAFO

II. BASIC DESIGN OF AAFO

In order to walk forwards with a fixed ankle, a mechanism is needed to replace the function of the human ankle, for example, a mechanism for rotating the leg around a fulcrum. Figure 1 shows the basic structure used in this study [1]. In the figure, a weight support 1 can be turned on a hinge 2 by an actuator 3. If the patient wants to stand upright, then the weight support 1 should be kept open to provide support. On the other hand, if the patient wants to propel his leg forward, then the weight support 1 should be closed. When a person's weight is loaded on his heel the result is momentum around the heel. Then the leg inclines and the toes can descend to the ground. With the approach reported here, the big toe can support the patient's weight, and this can be transferred to allow a forward step to be taken. If the patient wants to stand

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upright,. then the weight support 1 should be kept open to provide support.

A prototype AAFO was constructed using the basic structure. The sole of a commercially available AFO (Kawamura GISHI Co., Ltd.) was equipped with an actuator whose outline mechanism is shown in Fig. 2. The shaft of the servomotor (GWS11H) is connected to a perpendicular board by a wire. The board is connected to the weight support by a hinge. When the servomotor pulls the wire, the weight support closes. When the shaft returns to its original position, the bar spring recovers and the weight support opens. The servomotor does not need a large torque because the weight support is controlled so that it switches on and off during the swing phase of the gait.

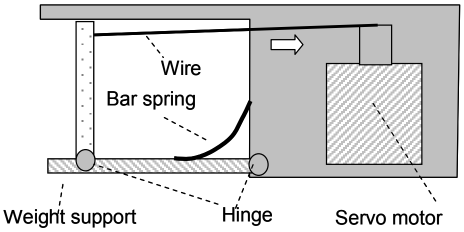

Fig.2 Actuator mechanism

III. AUTOMATIC CONTROL SIGNAL FOR ACTUATOR

A. EMG signal

Fig.3 Experimental setup

Gait trials with an able-bodied subject were performed on a treadmill, and the performance with and without the AAFO was compared. LED light markers were attached to the right side of the subject's body, and three-dimensional movement was measured using stereo video cameras. EMG signals were measured at the same time. A 3-D KineAnalyzer (KISSEI COMTEC CO., LTD) was used for the motion analysis. Figure 3 shows a trial where the subject had an AAFO fitted to his right leg and the ankle fixed with plantar flexion. The red line shows a stick picture of the right side. In comparison with a conventional AFO, the subject could walk faster without the help of crutches.

Figure 4 compares the joint kinematics without an orthosis (blue lines) and with the AAFO (red lines). The joint angles for ten walking cycles were measured and averaged. The hip angle graph indicates that both figures are similar, however the red values are about 10 degrees larger than the blue values. This difference may arise from the body posture because zero degrees represents a standing posture. The knee angle distribution when wearing the AAFO is about 5 degrees smaller than that without an orthosis because the walking stride is shorter. It is clear that the ankle data for these two conditions differ greatly because the ankle has a fixed plantar flexion with the AAFO.

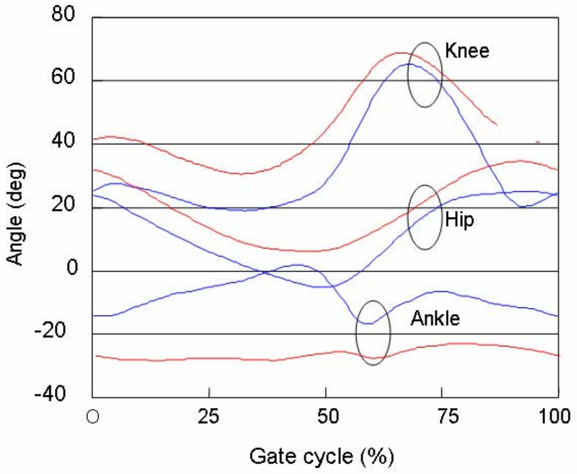

Fig. 4 Average angles of leg flexion/extension joints over the gait cycle, beginning and ending at heel strike. The data is from motion in the sagittal plane (flexion/extension).

Automatic control of the electric actuator for the AAFO is indispensable for practical applications. One control signal candidate is the EEG signals of the leg [9]. Electromyographic (EMG) activity was sampled from the muscles of the right leg at 1000 Hz using standard surface electrodes. The muscles were the tibialis anterior (T-EMG, ankle dorsiflexion), the soleus (S-EMG, ankle plantar flexion), the rectus femoris (R-EMG, knee extension) and the hamstrings (H-EMG, knee flexion). Full-wave rectifications of the EMG voltage for ten walking cycles were measured and averaged. The relationship between the muscle EMG voltage and the gait cycle are shown in Fig. 5-1 and 5-2. The gait cycle consisted of a standing phase beginning at gait cycle zero and a swing phase. In comparison with the ankle angle in Figs. 4 and 5-2, the blue data around the swing phase in both figures have two peaks. This coincidence with respect to the pattern indicates ankle movement induced by the soleus muscle without an orthosis. On the other hand, for the red data (i.e. with the AAFO), this relation is not clear. To clarify the relationship quantitatively, cross-correlation coefficients were derived and the results are shown in Table 1.

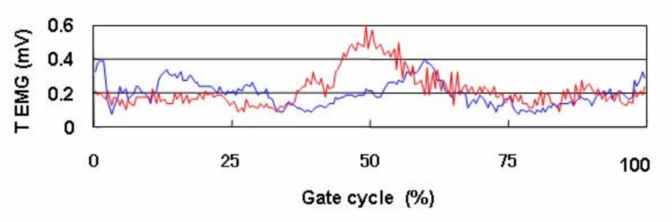

Fig.5-1 Tibialis anterior activation pattern

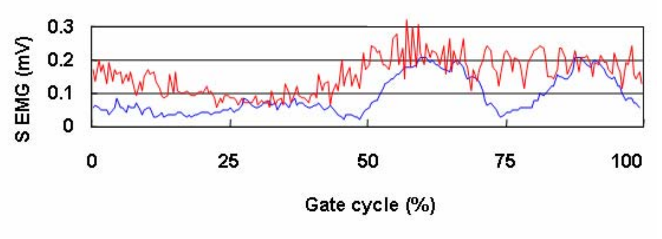

Fig.5-2 Soleus activation pattern

Table 1 Cross-correlation coefficients between EMG and knee angle

	No orthosis	With AAFO
Tibialis anterior	0.57	0.04
Soleus	0.50	0.55

Without an orthosis, the muscle activation pattern and the knee angle had a cross-correlation coefficient of more than 0.50. When the patient was wearing the AAFO, the coefficient for the tibialis anterior was only 0.04. The reason for this is unclear, however, the movement of the big toe when walking with the AAFO might affect the EMG of the tibialis anterior. In this case, the EEG signals from the lower leg were unsuitable for servomotor control. The cross-correlation coefficient between the EEG signals from the upper leg and the knee angle was more than 0.5 and was suitable for servomotor control. Therefore, placing electrodes on the upper leg is a possible approach to automatic actuator control. However, attaching and removing the electrodes is not very convenient

B. *Leg load signal*

The leg load changes according to the gate cycle. The leg load can be detected by foot sensors. The relationship between the gate cycle and the leg load is simple and clear. The leg load is a candidate for automatically controlling the actuator during the gate cycle. There are many types of load sensors. I selected and compared the performance of three typical sensors. Initially, strain gages were used as load cells and they are small and very precise as regards measuring the absolute value at a point. However, they are very sensitive to impact and not appropriate as leg load sensors because it is difficult to eliminate impact when walking. The second, a film sensor (FlexiForce) is very thin and useful for measuring the load beneath a foot. It is 0.2 mm thick and the sensing area is 9.5 mm in diameter. However, experimental results revealed that the measured leg load varies greatly because it is difficult to place one's foot repeatedly on exactly the same point on the sensing area. The third, an air pressure sensor can withstand impact, and the sensing error is small because it measures the average pressure. It has been used as a foot pressure sensor to control the actuators of powered suits [8]. Figure 6 shows experimental results for the performance of the pressure sensor and the FlexiForce. In the experiment, the termination of a coiled vinyl tube with a 5 mm outer diameter was connected to a pressure sensor (Fujikura FXM-025kPGR) with the other termination sealed. Also, a FlexiForce (1-617-464-4500) was sandwiched between 2 mm thick rubber sheets . The use of the sheet corresponds to an expansion of the sensing area. Both sensors were installed beneath the heel of the right foot, and weight was applied at approximately two second intervals. The figure indicates that both sensors were effective in estimating the leg load . However, the FlexiForce output varied depending on its arrangement. This phenomenon may depend on the structure and material, as well as the length of the AFO shoe. Finally, two air tubes were installed in a shoe to measure the toe pressure and heel pressure, simultaneously.

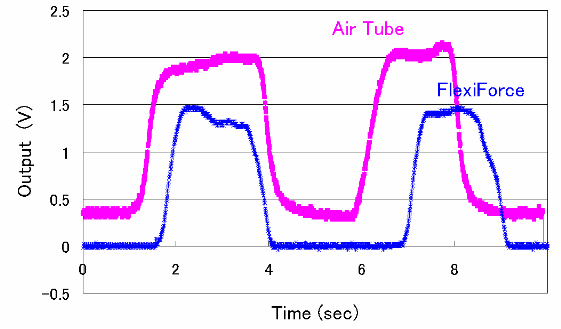

Figure 6 Comparison of measured leg loads

Experimental results revealed that the total toe and heel pressure represented the subject's weight well. Consequently, I decided to try using an air pressure sensor to measure the leg load of an automatic control AAFO.

IV. AUTOMATIC CONTROL AAFO

An automatic control circuit was constructed for the prototype 2 AAFO with foot pressure sensors. Figure 7 shows the front view of a handmade circuit in a control box. Two pressure sensors (Fujikura FXM-025kPGR) were arranged at the bottom left and right of the circuit and connected to the sensor tubes. Figure 8 shows the arrangement of the air pressure tubes for toe and heel, respectively, on the surface of the AAFO. The top center of the figure shows a rear view of the control box, which houses 4 AA batteries and a 006P battery. The total electric current consumed by the PIC and sensors is 30 mA. A 006P alkali battery (500 mAh) can operate for more than 16 hours.

The servomotor current is supplied by the four AA batteries, which are easy to replace. The control box is attached to the rear of the AFO and the servomotor is attached at the bottom of the AFO. Table 2 shows the AAFO specifications. The electric circuit weighs 280 grams including the case and batteries. The servomotor and its housing weigh 190 grams. The total AAFO (AFO, controller and actuator) weighs only 1700 grams. This is a practical weight for daily use.

Table 2 AAFO specifications

Actuator dimensions	130 mm (L)x100 mm (W)x33 mm (H)
Weight	Circuit + batteries 280 g Servomotor + housing 190 g AAFO total 1.7kg
Power supply	DC 5V (4 AA and 006P batteries)
Motor	Servomotor
Sensor	Air pressure sensor

The controller is programmed so that the actuator is normally open and it closes only when the leg load is applied to the heel for longer than a given time, for example1 second, because frequent on/off switching while walking is noisy and pointless. This time control is not only practical and comfortable but also effective in conserving battery energy. When the subject stops walking and stands still, his weight is shared by his toes and heels as long as he stands still. The weight support only opens when he intentionally stands still. If he lifts the leg equipped with the AAFO, the load sensor detects that the leg is in the swing phase and closes the weight support immediately. A practical fixed time and control sequence must be determined experimentally. In this report, I have concentrated on the automatic AAFO structure and mechanisms; the control sequence and program must be studied further.

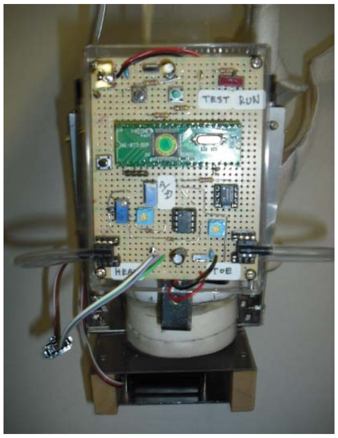

Fig.7 Electric circuit

Fig.8 Air pressure tubes

V. CONCLUSION

An automatically controlled active ankle foot orthosis (AAFO) for the treatment of a ruptured Achilles tendon was proposed. The EMG signals of limbs and leg load signals were compared as candidates for use in controlling the actuator. A gait trial on a treadmill undertaken by a subject wearing the AFO revealed that the cross-correlation coefficient was small between the ankle angle and the EMG signal of the lower leg. Also, an air pressure sensor and a film sensor were tested and the former was found to be useful for detecting the leg load. A control mechanism depending on the leg load was simple and its performance was stable.

Consequently, an automatic control system utilizing load was proposed and a prototype circuit was fabricated. The actuator switches between the upright state and the step forward state immediately depending on the leg load.

The tested AAFO is a prototype designed for a feasibility study. Further study is required as regards appropriate control of the actuator and will involve comparing the merits and demerits of EMG signals and leg load signals.

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