Intelligent Ankle-Foot Orthosis by Energy Regeneration for Controllable Damping During Gait in Real Time

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Kyoko Shibata[1], Yoshio Inoue[1], and Hironobu Satoh[2]

[1] Kochi University of Technology, Tosayamada, Kami, Kochi, Japan
{shibata.kyoko,inoue.yoshio}@kochi-tech.ac.jp
[2] National Institute of Technology, Kochi College, Monobeotsu 200-1, Nangoku, Kochi, Japan
satoh@ee.kochi-ct.ac.jp

Abstract. Many hemiplegia patients use the ankle-foot orthosis (AFO) to prevent foot-drop when they walk. However, it is difficult to walk smoothly because conventional AFOs have high rigidity. In order to support natural gait of hemiplegias, in this study, a technique to regenerate energy is applied, and a new self-powered semi-active AFO combining a DC motor and a step-up chopper circuit is developed. In this method, it is possible to drive a long time safely and the damping on an ankle joint can be controlled. From gait experiments, this study show that developed AFO can be rotated the ankle joint smoothly, be charged battery by regenerating energy loss during a gait, and prevent foot-drop. Hence developed AFO can be expected to have high gait improvement effect than the conventional type. Furthermore, developed AFO shows high electricity recovery (86.5%).

Keywords. Medical and Welfare Assistance, Ankle-foot Orthosis, Semi-active damper, Energy Regeneration

1 Introduction

In natural normal gait, as shown in Fig. 1, with the appropriate braking force generated by working dorsal and planter flexors alternately, the rotation of the ankle joint changes. In view of energy, it is applied during toe-off timing, and it is consumed during other timing because the braking force is required. On the other hand, in the swing phase, hemiplegic patients cannot be taken the clearance between the foot and the ground (foot-drop), and be leading to stumble and fall, because they are difficult to generate a braking force by muscular weakness, etc. Therefore, conventionally, many hemiplegic patients mount ankle-foot orthosis (AFO) which are possible to suppress the movement by a fixed ankle joint. This braking force of plantar flexion is compensated, so foot-drop can be prevented. The use of conventional AFO is effective to improve their gait. These are clinically well known. However, since conventional AFOs have large rigidity, cannot be freely rotated ankle, appropriate braking force is not generated, in other words, the patient performs an unnatural and high energy consumption gait. This causes hyperextension of the knee joint during heel ground. So, because hemiplegic gait differ significantly from healthy gait, even using conventional AFO, rehabilitation effect cannot be obtained to reacquire a smooth gait.

Here, if an AFO that is intelligent that can variably control the resistance (damping) of the ankle joint according to the gait state, it is considered that the patient's gait motion becomes smoother, and more so that continue to use to lead to the restoration of gait function by learning the natural gait. However, when the function of the orthosis becomes higher, secure energy source is required. Therefore the increase in weight and size and the restriction of use time or space become new problems. For AFO with a variable damping ankle, so far, the orthosis with a passive non-linear hydraulic damper[1], semi-active orthosis by MR fluid[2], active orthosis by a servo motor[3], etc. are commercialized or studied. In these, effect of gait improvement have been reported, however, it is difficult to be satisfied both to ensure the natural gait and energy sources.

For these problems, in this study, new AFO system (iAFO) is developed by the semi-active damper using the DC motor and the energy regeneration with the step-up chopper circuit. It can be controlled the damping of rotated ankle joint depending on the gait state, and driven a long time. This iAFO allows for active rehabilitation of continuous long-term. A single iAFO can be applied for of course rehabilitation at hospital, home rehabilitation (Fig. 2) and life support. In Fig. 2, time-series data of the ankle joint angle are transmitted in real time to the server from the controller including iAFO. This data can be monitored to doctors or physical therapists in a hospital, and patient can be instructed in remote by them. Also, if necessary, it can be derived that the patient gait becomes more natural gait by automatic adjusting the strength of the controllable damping by real time remote feedback. Since this is become self-training, it is considered that effect of gait functional recovery is large. Further doctors or patients can check the progress of the recovery of gait ability at any time with cloud service.

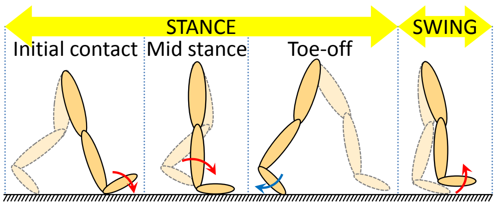

Fig. 1. Normal gait

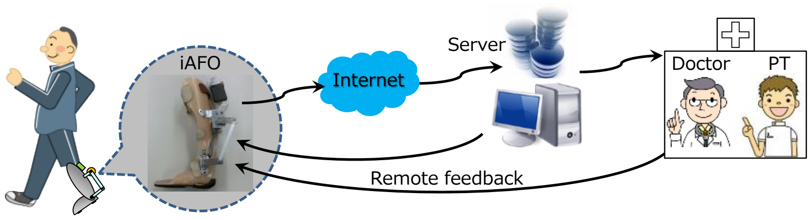

Fig. 2. Overview of remote feedback system including iAFO

In this report, first, the overview of iAFO is described. Then, from gait experiments using iAFO, the results of investigation is shown about the damping variable control, charging of a battery, gait improvement, and the power recovery ratio.

2 Basic characteristics of the prototype

In this study, the DC motor and the set-up chopper circuit are combined, whereby rotation damping is controllable and energy is regenerated.

The prototype iAFO is shown in Fig. 3. The controller which is consisted of the microcomputer and the set-up chopper circuit[4] is attached to the plastic AFO with an ankle joint can be rotated freely. The DC motor is rotated through links and gear (159:1) depending on the motion of the ankle joint. The gait state (Fig. 1) is determined by the output of the two pressure sensors attached to the foot, and the rotation damping ankle is controlled. Specifically, the damping magnitude is smaller in order to soften the movement of the ankle in the stance phase, and is larger in order to restrict the movement of the ankle in the swing phase. Depending on the gait state, ON circuit without battery and OFF including battery of the set-up chopper circuit is switched at high frequency by the controller. The average current per unit time flowing through the DC motor by controlling duty ratio of the PWM control is changed, therefore, the appropriate braking torque is generated. That is, it is possible to obtain the semi-active damping for plantar flexion or dorsiflexion. At this time, the energy due to the rotation of the DC motor is converted into electrical energy, it is charged in the battery by the step-up chopper circuit, and the driving force required for the control is obtained. The total weight of iAFO including the battery is 1.110 [kg].

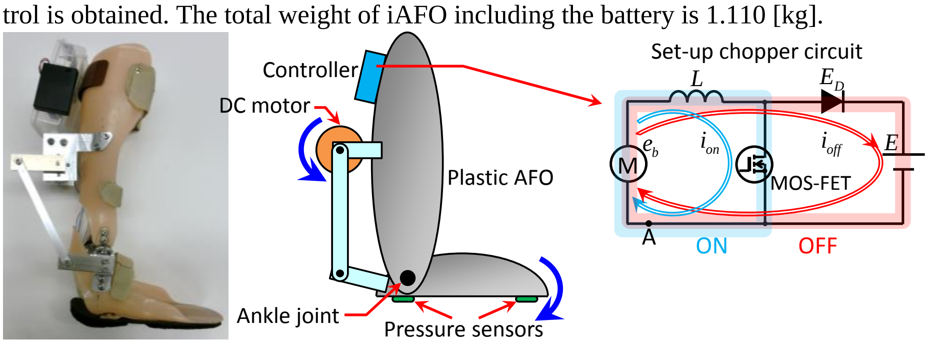

Fig. 3. iAFO

3 Continuous gait experiments

3.1 Consideration of gait improvement

A healthy subject is wearing iAFO on his right leg, and imitates a hemiplegic gait. He is continuously gait at a velocity of 3[km/h] using a treadmill. In this experiment, duty ratio is set to 0.4 to slightly soften the rotation damping of the ankle joint at the initial contact, 0.1 to soften at the mid-stance or 0.9 for tightly at the toe-off timing and swing phase.

Fig. 4 is time history of the ankle angle per one gait cycle when (1) wearing the conventional AFO, (2) wearing iAFO, (3) normal gait (bare foot).

At results, since it is not open large ankle angles when fitted either AFOs, it can be seen that it is possible to prevent foot-drop. Also, because the ankle of iAFO can move freely, the range of ankle angle change of iAFO is larger than conventional AFO. In other words, it is considered that gait difficulty due to the rigidity of AFO has been improved by the proposed method. In addition, gait time is longer, that is, gait improvement is shown since the step length is increased.

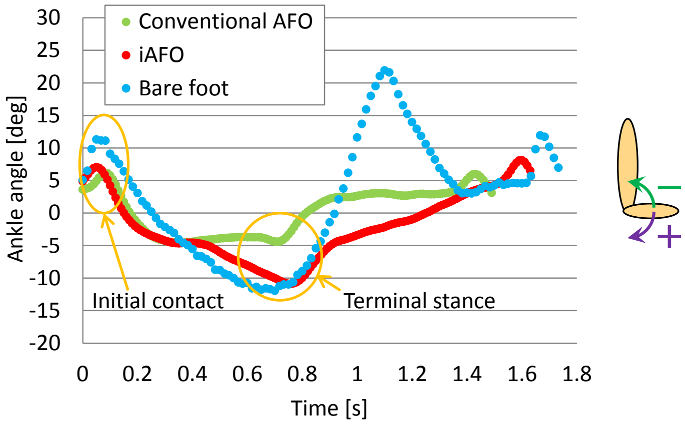

Fig. 4. Ankle angles at gait experiments

3.2 Consideration of electric power recovery ratio

Using two 5[V] batteries, one connects to the microcomputer and sensors for power supply and other connects to the step-up chopper circuit for charging. Fig. 5 shows a part of the current flowing from the power supply for the battery, Fig. 6 shows a part of the current flowing into the charging battery.

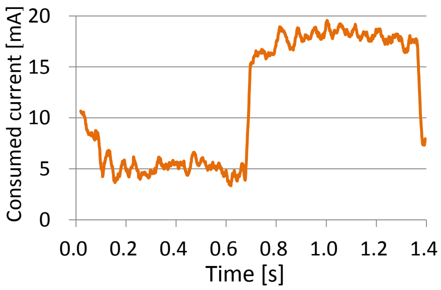

Fig. 5. Consumed current (One gait cycle)

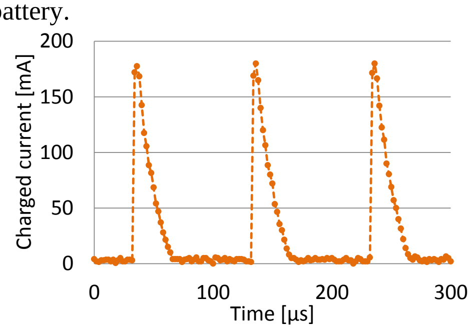

Fig. 6. Charged current

In this paper, power recovery ratio is defined the percentage of charging power to the power consumption. By an average value of five measurements, power consumption is 57.36[mW], charging power is 49.60[mW]. Therefore the power recovery ratio in this gait is 86.5%.

4 Conclusion

In this study, it is proposed to assist a hemiplegic gait using the AFO with the DC motor and the set-up chopper circuit. Developed iAFO can be controlled to the semi-active damping of ankle joint depending on the gait state. At the same time, iAFO is capable of driving long time using by regenerated energy that is absorbed by the ankle joint motion into the small battery.

In this paper, prototype iAFO are produced, and gait experiments with healthy person are performed using iAFO. As a result, it is confirmed that it is possible to charge the battery, it is possible to prevent foot-drop, further, it is possible to change the ankle joint smoothly compared to the conventional AFO, and the power recovery is high ratio. Thus, effectiveness of this proposed system is shown.

In the future, based on the ankle joint angle from the encoder of the DC motor, this study deploy to the cloud services, such as remote monitoring by orthopaedists or physical therapists and real-time damping adjustment.

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