Active Lower Limb Orthosis with One Degree of Freedom for Paraplegia

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Keywords: Assistive Robot Device, Lower Limb Orthosis, Active Control, Mechanism of Linkage, All in One.

Abstract: This paper describes a new design of active lower limb orthosis which is called as oneDHALO (one-actuator Drive Hip and Ankle Linked Orthosis). The oneDHALO has a linking mechanism which connects both ankle joints with a medial hip joint and an actuator which drives the rotation angle. The joints linkage mechanism keeps feet always in parallel with the floor to avoid stumbling, and assists swinging of the leg. One servo motor has been introduced to assist and control the movement constrained by the mechanism. To match the active movement to walking phase, optical sensors have been introduced at the soles for detecting the distance between the feet and floor. The control device which consists of internal communication system, sensor interfaces and a single board computer (Raspberry Pi) is designed for all in one with the mechanical part of the orthosis. The system has achieved continuous walking based on the feedback signals from the sensors. This paper reveals the preliminary experimental results of the system to show the good points of the design.

1 INTRODUCTION

Several hip-knee-ankle-foot orthotic systems have been developed for the bipedal locomotion of paraplegics (Rose, K. G., et al., 1979). However, most of existing orthotic systems have problems in use; 1) a large energy consumption for bipedal walking on flat floor (Stallard, J. and Major, E. R., 1998), 2) bulky, 3) difficult to don/doff (Merati at al., 2000). To solve those disadvantages, recent studies for lower limb orthoses have aimed at the usability with simple and lightweight design (Kirtley, et al., 1996). Problems of those systems are that the strides were short because the characteristic of the horizontal rotation of the pelvis in the orthosis, otherwise the patient feel pain (Saito et al., 1996, 1997). Genda et al. (2004) proposed an orthosis, HALO (Hip and Ankle Linked Orthosis), which has a link mechanism connecting ankle joints with a medial single hip joint. HALO partly solved the problems of short strides or large rotation of the pelvis (Genda et al., 2004). The orthosis allows the users to keep their both feet always parallel with the floor to avoid stumbling, and it assists the swinging of the leg when the contralateral ankle is fixed dorsally by loading. The energy consumption of the user is a problem of HALO remained unsolved. The consumption energy of the users was about five times larger than normal walking (Genda et al., 2007). To reduce the energy consumption of walking with HALO, the authors proposed an extension of HALO with one-actuator drive, which is called as oneDHALO in our previous study (Michal et al., 2017). In this paper, we describe a new software development system and an all-in-one design for oneDHALO.

The next chapter shows the mechanical configuration and the motion behaviour of HALO. In chapter 3, the extension with one actuator has been proposed for the all in one system including the power source. The active control system and the software development system are proposed in chapter 3. The comparison with another active assistive devices is also given from the aspect of the usability, performance and cost in the chapter. Chapter 4 shows the concept of motion planning and the preliminary experimental results. The role of each subsystem and the system integration seeking suitable active motions are explained. The preliminary experimental results of the system are also shown to understand the good points of this new design in chapter 5. The concluding remarks are given in the final chapter.

Sunada, T., Obinata, G. and Pei, Y.
Active Lower Limb Orthosis with One Degree of Freedom for Paraplegia.
DOI: 10.5220/0007959905040509
In *Proceedings of the 16th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2019)*, pages 504-509
ISBN: 978-989-758-380-3

2 MECHANICAL CONFIGURATION OF HALO

The features of HALO come from the link mechanism and the connections between the medial hip joint and the ankle joints by Boden wires. The hip joint has two pulleys which rotate independently around the same hip joint axis. Each pulley is connected with the contralateral knee-ankle-foot orthosis. One Boden wire is set for coupling the ankle joint with a certain moment arm to the same side pulley at the hip joint. It is noted that the pulley is combined with the other side link, which is shown in Figure 1. The wire of the other pulley is set in similar manner for the other couple. When dorsal flexion at one ankle occurs with loading, the wire connected to the heel of the same side pulls and rotates the pulley of the hip joint connected with the contralateral knee-ankle-foot part of orthosis, and then the generated torque at hip joint assists the other side leg in swinging forward.

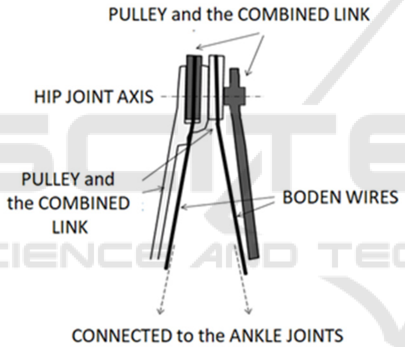

Figure 1: Medial hip joint and the connections.

The Figure 2 explains the operation of Boden wire in sagittal plane. The lower bar $\boldsymbol{B_l}$ is connected to the foot link and rotates around the axis O; the upper bar $\boldsymbol{B_u}$ is connected to the contralateral link system and rotates around O'. The Boden wire **W** connects the two Bars to transfer the rotation of $\boldsymbol{B_l}$ to the upper bar $\boldsymbol{B_u}$ (See (a) in Figure 2). The tilt occurs, then the loading around O by the foot link keeps $\boldsymbol{B_l}$ in the horizontal orientation. This causes that the bar $\boldsymbol{B_l}$ pushes the bar $\boldsymbol{B_u}$ up $\boldsymbol{r_l}\,\theta$, where θ is the rotation angle of $\boldsymbol{B_l}$. When $\boldsymbol{r_u} = \boldsymbol{r_l}$, the bar $\boldsymbol{B_u}$ rotates the same angle θ. This means that the bar $\boldsymbol{B_u}$ is always parallel to $\boldsymbol{B_l}$ (See (b)). If $2\boldsymbol{r_u} = \boldsymbol{r_l}$, the bar $\boldsymbol{B_u}$ rotates double (See(c)). In this case, the contralateral link system connected to the bar $\boldsymbol{B_u}$ as shown in Figure 2 is in a symmetric position with respect to the line A-A'. The Boden wire of the contralateral link makes the lower bar in parallel to

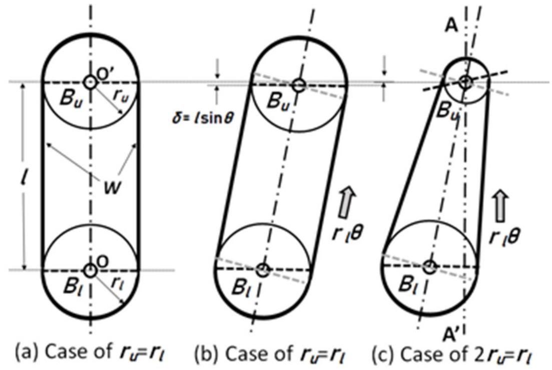

Figure 2: Operation of Boden wire.

the bar $\boldsymbol{B_l}$. When $\boldsymbol{r_u} = \boldsymbol{r_l}$ and the link works as supporting leg, the clearance to the floor bigger than $\boldsymbol{l}\sin\theta$ will be required for the swinging leg (the contralateral link). In the case of $2\boldsymbol{r_u} = \boldsymbol{r_l}$, the swinging leg (the contralateral link) declines oppositely the same angle as the supporting leg; the lower bar is parallel to the floor. Moreover, the height of the swinging leg is equal to the supporting leg. This causes that zero clearance is required for the swinging leg.

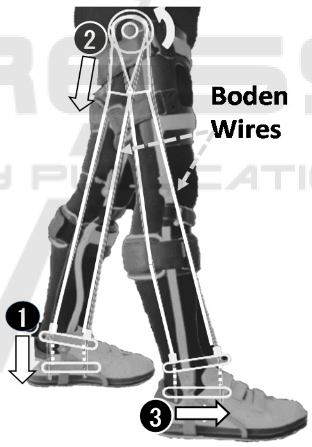

Figure 3: Schematic illustration of mechanism operation.

The illustration in Figure 3 explains the way in which the link mechanism works as an assistive device for walking with paraplegia. When the upper body inclines forward, a certain amount of dorsiflexion torque is generated at the ankle joint because the body weight is loaded on the supporting leg. First, the torque is converted by the lower bar to the force, which pulls the wire to rotate the upper bar which is just the pulley at hip joint. Second, the torque generated at the hip joint rotates the contralateral knee-ankle-foot orthosis (the swinging leg). Third, it results in the forward swing of the contralateral leg.

Moreover, the loop connection of the Boden wire keeps the lower link at the ankle joint parallel to the floor as explained above with Figure 2. This means that the user can enjoy his/her foot clearance of the swinging leg without being anxious while walking with HALO.

3 CONFIGURATION OF ACTIVE CONTROL SYSTEM

In previous study, Genda et al. (2007) revealed the pelvic rotation with Loftstrand crutches helped enough for the physiologically normal level by the gait analysis with HALO in the experiments. However, the consumption energy of the user was five times larger than normal walking. In this paper, one servo motor with a communication port has been introduced to assist and control the movement constrained by the mechanism of HALO. All in one orthosis including power source is the target for our new design. There are several ways when active control is applied to HALO mechanism. An active extension of HALO with two electric motors was proposed (Lee et al., 2015), which is called as powered HALO (pHALO). In the extension, the problem is solved how two motors are set into the one degree-of-freedom mechanism. The direct introduction of two motors in the two Boden wires of HALO's both legs provides a function for changing the relative positions between the three links at the two joints, ankle and hip. The function was used for

Table 1: Comparison of HALO and powered HALO (Obinata, G., et al., ,2015).

	Stride length[m]	Gait speed [m/s]	Displacement of CoG [m]	Power [Nm/s]
HALO	617.9 $\times 10^{-3} m$	225.5 $\times 10^{-3} m/s$	51.6 $\times 10^{-3} m$	12.9 Nm/s
pHALO	637.9 $\times 10^{-3} m$	283.5 $\times 10^{-3} m/s$	25.7 $\times 10^{-3}$	7.84 Nm/s
cf. [%]	+3.23 %	+5.76 %	-50.2 %	-39.2 %

pushing up the supporting leg to decline the upper body forward in pHALO. Experimental results of such a function showed the advantageous effect on strides, gait speed, fluctuation of body COG, mechanical power as shown in Table 1. The results looks good; on the other hand, the total weight of the device including the orthosis was more than 12Kg. Taking out the link mechanism with Boden wires and setting four motors at hip joint and at knee joints make a multi-actuated assistive device. Device called as Rewalk (ReWalk Robotics, 2011) is a typical and successful one with four actuators. If the control scheme is good for the user, Rewalk may work well because it has enough degree-of-freedom to achieve an ideal motion for the user's severity of impairment. However, the weight is 22Kg and it is expensive. Lighter weight of assistive device is desired for users' handling and make it possible bring the device everywhere. To reduce the weight, only one motor has been introduced into HALO in this pa per. With one motor, the movement of HALO which is described in Chapter 2 will be compensated by

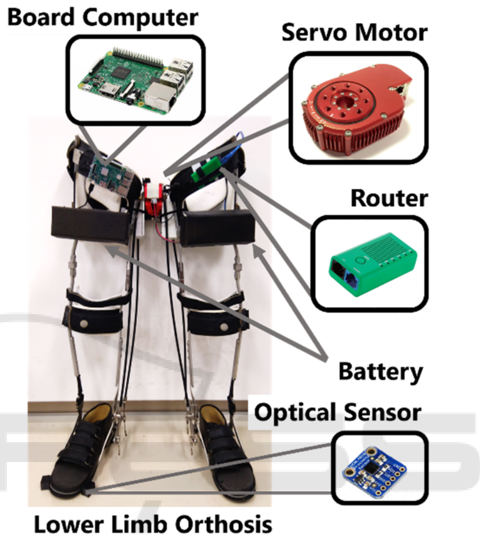

Figure 4: oneDHALO, the actuator and the sensors.

appropriate motor control scheme. The preliminary results of one-drive HALO (oneDHALO) showed the similar effects as powered HALO with two motors (Michal et al., 2017). However, the device can work only in the case that the control signal to the motor and the electric power are provided from outside through wires. In other words, the subsystems: the controller, the sensor interface and the power source were located outside of the HALO mechanism. On the other hand, all in one system has been achieved including the mechanism, the sensors, the actuator, the controller, and the power source in a new design of oneDHALO. To match the active movement to walking phase, optical distance sensors (Ambient light sensor, VCNL4010) have been introduced at the soles of feet. The mechanical part, the actuator, the power source, controller and the sensors are shown in Figure 4. The control system which consists of internal communication system (Ethernet), interfaces for sensors and a single board computer (Raspberry Pi) is designed for all in one with the mechanical part of the orthosis, which is shown in Figure 5. The sensors have infrared emitter to analyze the proximity, and transmit the measured distance to the board computer (main controller) by I2C communication interface. The signals from the sensor are used for the main controller to decide which leg is supporting one. The total weight including the mechanical part and the power source is 7.1kg. The control system includes a router of TCP/IP, which

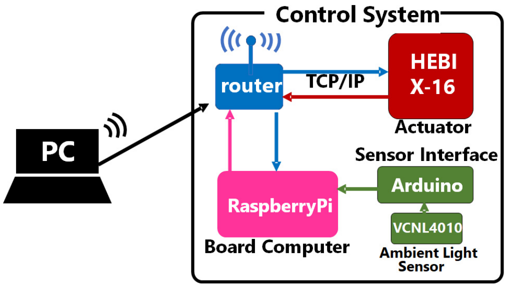

Figure 5: Software development system for oneDHALO.

communicates with a high specification personal computer through Wi-Fi. The PC enjoys several kinds of high-level programming languages for developing the control algorithms of the active assistive orthosis. In this design, the PC is used only for the software development. The developed program for controlling the active orthosis in real time will be sent to the board computer, and be executed locally. The actuator (HEBI X8-16, HEBI Robotics) is an Ethernet-enabled device that integrates a brushless motor, gear-train, a rotary encoder and control electronics into a compact package. It runs on standard DC voltages and communicates using standard 10/100Mbps Ethernet. The module run a real time operating system in the modules itself that process commands and feedback at 1kHz. The actuator accepts commands and responds to requests to feedback through the network.

4 MOTION PLANNING AND EXPERIMENT

4.1 Motion Planning

Assume that right leg is in supporting phase with oneDHALO. When the motor gives torque of a positive magnitude to swing the left leg forward, this action assists the user's walking forward. In this situation, the torque of a negative magnitude interferes walking forward. Hence, the controller must detect which leg is in supporting phase. For this purpose, proximity and ambient light sensing modules (VCNL4010) have been introduced for measuring the distance between the feet and the floor. The distance below a certain value means that the foot is in supporting phase. To avoid malfunction of the sensors due to unevenness of the floor surface, four sensing modules are set for one foot. To plan the motion of motor, the following parameters have to be defined: the stride, the cycle time, and the assist level of walking with the actuator. These parameters define the pattern of hip joint angel while walking as in Figure 7, or our simulation technology can generate a suitable pattern for the hip joint angle (Obinata et al., 2015). Assume that $\boldsymbol{h^*(t)}$ is a cyclic function desired for the hip joint. The following control system is considered to achieve the desired motion of the hip joint (See Figure 6). The controller is a simple position controller with P, I, D elements for hip joint angle $\boldsymbol{h(t)}$. The generated torque of hip joint is the summation of the motor torque and the passive torque generated by loading on the supporting leg. The assistive level of active control can be adjusted by tuning the controller parameters. The level of active control $\boldsymbol{L_a}$ is defined as follows:

$$L_a = \int_0^T |t_a(\tau)| d\tau \,/\, \int_0^T |t_p(\tau)|\, d\tau \qquad (1)$$

The passive torque can be considered as a disturbance for the controller. If the passive torque $\boldsymbol{t_p(t)}$ is satisfactory and enough to generate exactly the joint motion $\boldsymbol{h^*(t)}$, the active torque $\boldsymbol{t_a(t)}$ generated by the

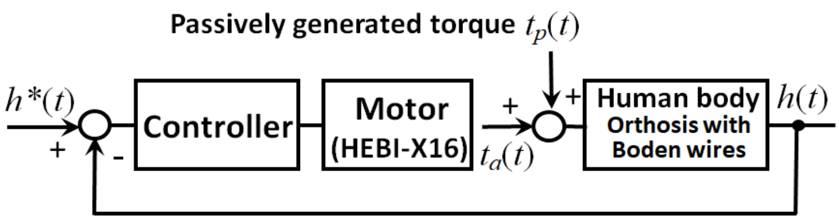

Figure 6: Proposed control system.

motor takes zero. If the passive torque $\boldsymbol{t_p(t)}$ is short, then the active torque $\boldsymbol{t_a(t)}$ compensates to achieve the joint motion $\boldsymbol{h^*(t)}$. Therefore, if we can define available reference joint angle $\boldsymbol{h^*(t)}$ as the reference,the control system automatically achieves the required torque by compensating for the passive torque. From the energy efficiency viewpoint, the timing for applying $\boldsymbol{h^*(t)}$ to the control system has to be matched to the generated passive torque. For this purpose, the phase matching between the passive torque and the reference joint angle is important. The sensors at feet for detecting walking phase can provide the signals for the phase matching of the reference joint angle $\boldsymbol{h^*(t)}$ to the passive torque.

4.2 Experiment

Operation tests with the control system described in the former chapter were conducted. The tests were on the tracking performance of angle position with a sinusoidal reference input and on the timing problem with signals of the proximity sensors. The tests was conducted without any load on the actuator. The tracking performance of joint angle to the reference was near perfect. The result is shown in Fig. 7 with the signals of the proximity sensor. It seems sufficient that the device achieves a certain tracking performance and provides enough assistive swing force to the user. The control program made the actuator start when the measured distance from the floor of the swinging leg exceeded 2mm. This is the typical usage of the proximity sensor. If the actuator starts before the swing leg leaves the floor, it may cause turning in situ. Signals from eight sensors (four sensors per one foot) can be used to estimate upper body movements of the user. Such estimation may be useful to match the active assistive torque to the passively generated torque specially for achieving the coincidence between the two torques.

5 CONCLUDING REMARKS

This paper proposes a new design of active control orthosis for paraplegic walking. After explaining the operation of the link mechanism, the configurations of the active control system and the software development system are given. The total weight including power source is 7.1kg, which is the lightest device of active lower limb assistive device for paraplegia in the world. This is achieved because the device has only one electric motor as the actuator and it works in concert with the passively generated torque induced by the shift of the upper body's CoG (center of gravity). Finally, the concept of motion planning and the preliminary experimental results are given in this paper. The tracking performance of active control system indicates enough potential for the purpose of assisting paraplegic walking in the preliminary experiment. Moreover, the proximity sensors introduced here will be useful for various control schemes, which may provide the adaptability to several types of the user. Defining and taking the

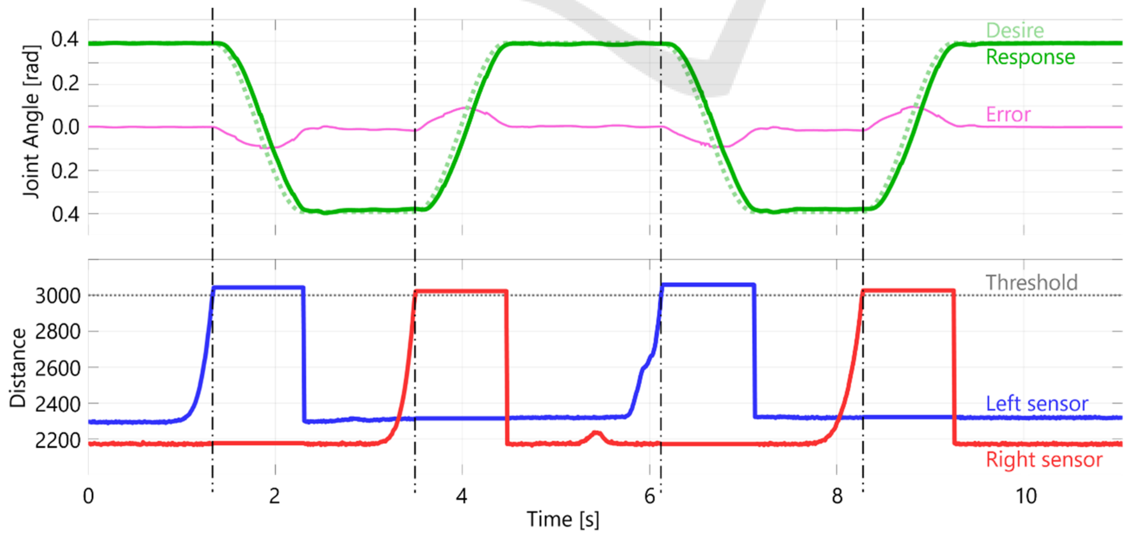

Figure 7: Reference, measured value of angle, and signals from the proximity sensors.

timing of the reference input for the device movement in concert with the user's action or intension is the main issue that should be solved in further research.

ACKNOWLEDGEMENTS

This works is supported by JSPS KAKENHI Grant Number JP16H03214. The authors thank to JSPS, for the grant and to Dr. Genda for his original idea of HALO.

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