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A New Powered Orthosis with Hip and Ankle Linkage for Paraplegics Walking

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***Abstract*— Several types of hip-knee-ankle-foot orthotic systems have been proposed for paraplegic walking during these decades. Hip and ankle linked orthosis (HALO) is compact one in those orthoses, which seeks to achieve a smoother-movement and user-easiness on its don/doff in paraplegic walking. The idea of HALO is to link two ankle joints with medial single joint via wires so that the orthosis keeps both feet always parallel to the floor while walking and assist the swinging of the leg. So as to reduce the consumption energy of HALO walking, we have introduced two actuators to control the ankle-joints angles in this paper. The actuators placed at hip joint in HALO allow the orthosis to have more degree-of –freedom and are able to provide a propulsive force the coupled user-orthosis system. The results of preliminary experiments with normal subjects show that the users can walk smoother and the proposed orthotic system will be able to reduce the users' consumption energy while walking.**

Keywords*— *paraplegics; gait orthosis; power assist; energy efficiency

I. INTRODUCTION

Standing and walking are able to provide much benefit for paraplegics such as preventing muscles contracture, joint spasticity and bone mineral loss, and as improving lower limb blood circulation and bowel function. Therefore, many efforts have been devoted to achieving supporting devices of standing and walking.

Hip-knee-ankle-foot orthotic systems such as hip guidance orthosis (HGO), reciprocating gait orthoses (RGOs) have been developed to make it possible for paraplegics to conduct bipedal locomotion [1], [2]. However, it is hardly to be expected that these orthotic systems achieve the high efficiency of locomotion as normal bipedal walking on flat floor [3]. Moreover, they are too bulky or difficult to don/doff so that many patients abandon them [4]. Recent orthotic systems have aimed usability with those simple and lightweight structures [5], [6]. In these systems, several discussions around the strides and horizontal rotation of the pelvis have been reported and some of them could partly solve the problems of short strides or large rotation of the pelvis [6], [7], [8].

One of the authors proposed an orthosis called "HALO" (Hip and Ankle Linked Orthosis) which has a link mechanism connecting ankle joints with a medial single hip joint. The orthosis allows the users to keep both feet always parallel to the floor while walking, and assist the swinging of the leg when the contralateral ankle is fixed dorsally by loading. The gait analysis on the experiments with HALO revealed that the pelvic rotation with Loftstrand crutches was small enough for the physiologically normal level [8]. However, the consumption energy per moving distance with HALO was five times larger than normal walking [9]. So as to reduce the consumption energy of HALO walking, we propose the extension of HALO to a powered one. The link mechanism of HALO puts the constraint on the hip joint and the ankle joints. We introduce two controllable actuators to control the angles of the two pulleys which are placed at hip joint in HALO. These actuators allow the orthosis to have more degree-of-freedom and to generate the propulsive force by itself. In this paper, we summarize the structure of HALO and describe the idea of the extension with actuators. The results of preliminary experiments with normal subjects show that smoother movements of walking are possible and the reduction of consumption energy can be expected.

II. MECHANISM OF PROPOSED ORTHOSIS

A. Mechanism

The mechanism of the orthosis consists of three parts: a medial single hip joint and two knee-ankle-foot orthoses (KAFO) with lockable knee joints and movable ankle joints. The both ankle joints are coupled with the hip joint by steel wires, which configuration is shown in Figure 1. The hip joint has two pulleys that have the same axis and rotate independently. The right pulley is connected with the left KAFO, and the left pulley is connected with the other side KAFO. One of the steel wires is used for coupling the ankle joint of one foot with a certain moment arm to the same side pulley at the hip joint. The other wire is used in similar manner in the other side. When dorsal flexion of left ankle occurs with loading, the wire connected to the heel pulls and rotates the pulley of the hip joint connected to the heel pulls and rotates the pulley of the hip joint connected with the right KAFO and

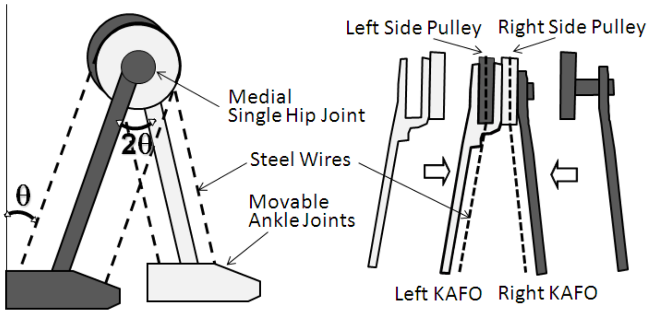
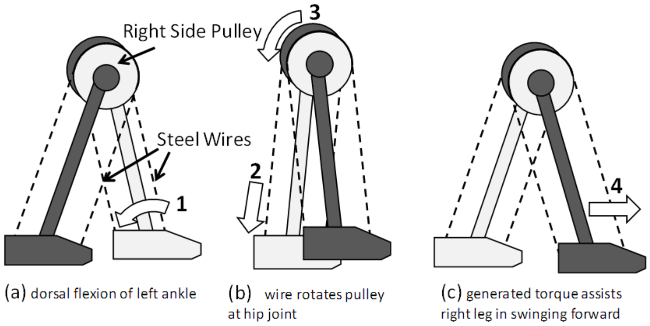


Fig. 1. Mechanism of HALO.



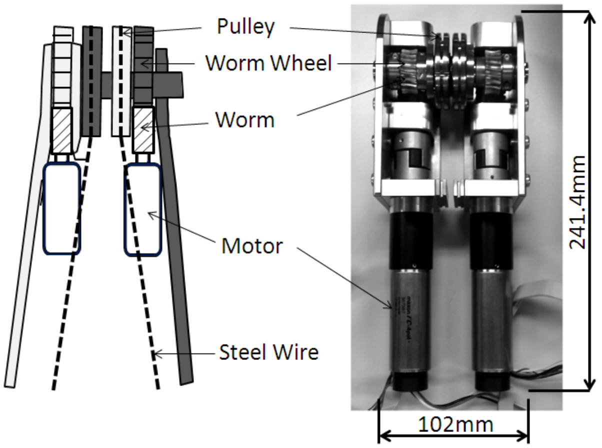
(a) dorsal flexion of left ankle (b) wire rotates pulley at hip joint (c) generated torque assists right leg in swinging forward

Fig. 2. Schematic illustration of orthotic behavior.

then the generated torque at hip joint assists the right leg in swinging forward. Figure 2 illustrates the motion pattern. The similar action occurs successively in the other side of leg and the alternative occurrence of these actions denotes a reciprocal gait. The rotation ratio between the ankle and hip joints is set at one to two so that the feet are always parallel to the floor during walking. To walk forward in this way a certain propulsive force should be generated by using Lofstrand crutches. The generated force is able to provide the torque of dorsal flexion at ankle and the appropriate forward sift of center of gravity of the body.

B. *Extension with actuators*

The previous experimental results showed that walking with HALO achieves smaller pelvic rotation, wider stride and larger cadence in comparison with another orthoses [9]. However, much energy consumption was required to handle the crutches for moving forward with this orthosis. The experimental evaluation on energy efficiency of walking with HALO was 17.0J/kg/m; on the other hand, it is about 3.2J/kg/m in normal walking [10]. Then, we consider in this paper to introduce electrical motors for reducing the energy consumption while walking with this type of orthosis. The idea for the extension with power devices is to control the rotation of the pulleys in the mechanism. The schematic illustration and the picture of introduced electrical motors in HALO are given in Figure 3. The motor axis is set to be parallel to the axis of femur. This means that the motor unit with the reduction gear and the casing has no boss protruded from contour of human body. The axis of the motor rotation is converted by a worm gear to horizontal direction in frontal plane which is the axis of the pulley. The independent control on the pulleys' positions by the electric motors makes it possible for the orthosis to possess three degree-of-freedom in total while the original HALO has only one degree-of-freedom.



(a) Introduction of motors (b) Photo of motors, gears and pulleys

Fig.3. Two power units introduced into HALO.

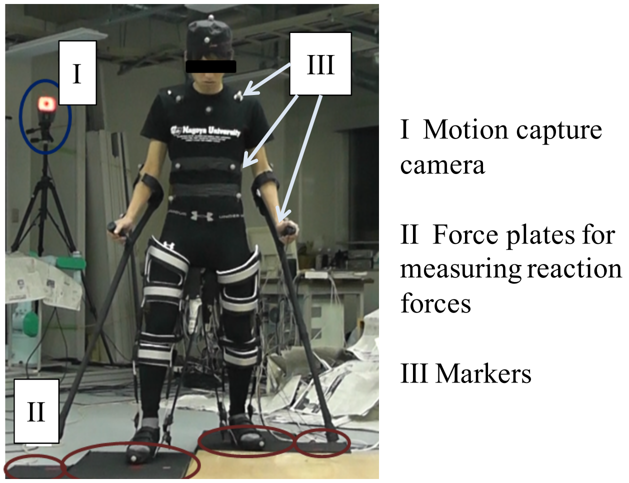


Fig. 4. Experimental setup.

Moreover, the motors are able to generate torques at ankle and hip joints through the pulleys. The design specification of maximum torque and maximum angular velocity with the motor are 68.6Nm and 275deg/sec at ankle joint, respectively.

III. PRELIMINARY EXPERIMENTS WITH NORMAL SUBJECTS

A. *Experimental setup*

To evaluate the gaits with powered HALO, three normal subjects were participated in the walking experiments. The ages, heights and weights were (23, 170cm, 53kg), (23, 168cm, 63kg) and (25, 170cm, 58kg), respectively. A Mac3D was used for the motion analysis, and four force plates were set on the floor for measuring the reaction forces of two legs and two crutches. Twenty six markers were attached to the body. Figure 4 shows the photo of the experimental setup and a subject with powered HALO.

B. *Control on actuator*

Although we can control the actuators in several ways, we take most simple control method with the sensor of angular velocity. The simple velocity feedback control with manually tuned feedback gain was applied for tracking a trapezoidal trajectory as the predetermined reference which is given by

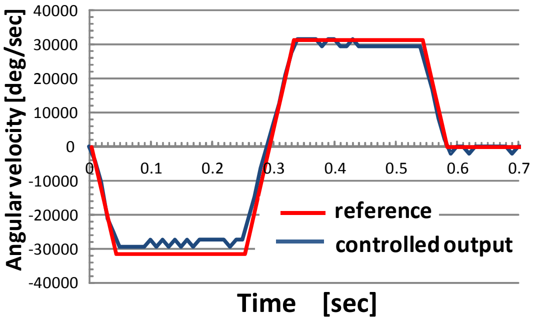
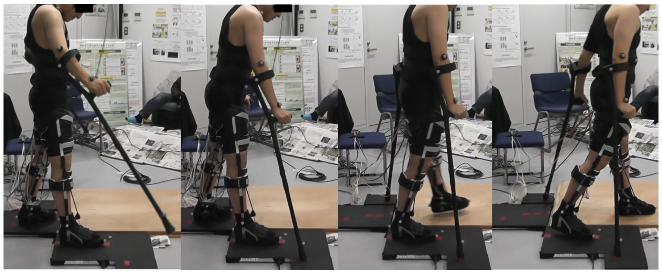


Fig. 5. Reference trajectory and control result of actuator.

Figure 5. We select the trapezoidal trajectory because it is typical for motor control to rotate a certain distance and to turn back to the original position. The sample result of the control is also given in Figure 5. This control provides a reciprocate rotation at the corresponding ankle joint. The plantar flexion of one ankle joint starts from the horizontal position and reaches to the tilted position with 7 degree, and then turns back during 0.6 seconds. The user can activate the motion of the actuator by turning on the switch placed at each grip of the crutch.

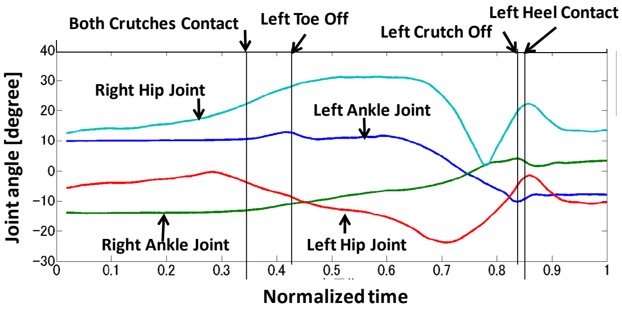
C. Experimental results

The procedure of one step walk which was suggested to the subjects is given by Figure 6. In Figure 6, photos (a), (b), (c) and (d) show the initial position, setting the crutches on floor, by dorsal flexing at right ankle joint and swinging the left leg by pushing with the crutches, and left leg touching down on the floor, respectively. The subject used the orthotic system as follows: Photo (a) was the initial position. At (b) the subject sifted his weight on the right foot in the dorsal direction. The ankle flexes dorsally and the wire connected to the heel was pulled. Then the generated wire tension pulled to rotate the pulley of hip joint that connects to the left leg. The pulley rotation swung the left leg at (c). Just before phase (b), the subject switched on the actuator which enabled the predetermined motor action for plantar flexion at right-ankle joint in the case of powered HALO. This action assisted the weight sift forward and reduce the pushing force amplitude of the crutches. Photo (d) was the final status of the one step and showed the touching down of left leg. The knee joints were locked during walking. The body wobbled in frontal plane to have a foot clearance of leg in swing phase. After enough practices for using the crutches and the power assistive motion at ankle joint, three subjects performed one step trials several times. Figure 7 gives the joint angles while the subject used HALO and powered HALO ("powered" means the usage of the motion generated by the actuator). The horizontal axes indicate the normalized times. It took 4.17 sec for one step with HALO and 3.33 sec with powered HALO. These durations are used as normalizing time in Figure 7. Step with powered HALO was faster than step with HALO. The right hip flexion of HALO fluctuates over 30 degree and varied twice in excess of 20 degree; on the other hand, one of powered HALO fluctuated once within 20degree. The left hip angle of powered HALO varied smoother than one of HALO (Compare the red lines in (a) and (b)). The difference between HALO and powered one came from the motion generated by the actuator which worked on the right leg.

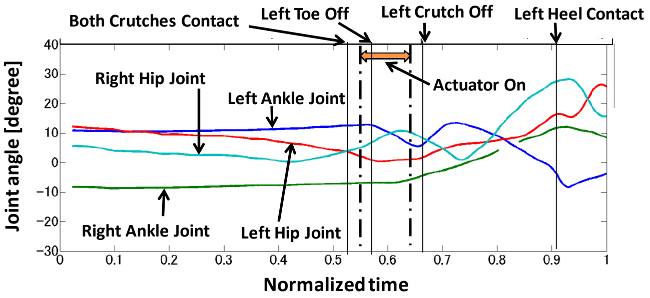


(a) (b) (c) (d)

Fig. 6. Procedure for one step of left leg.



(a) HALO



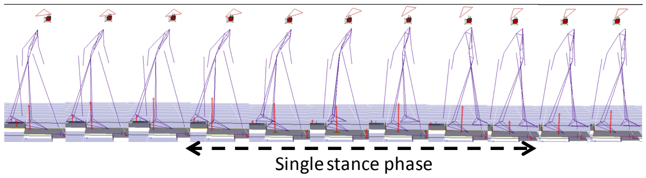
(b) Powered HALO

Fig. 7. Experiment results (joint angles).

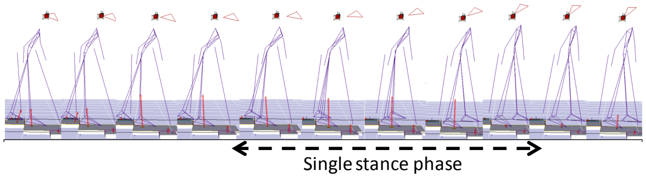
Figure 8 gives the stick figures for comparing the orientations of upper bodies in (a) HALO and (b) powered HALO. The upper body in HALO was bent backward in last half of single stance phase; on the other hand, the body went on with the head bent forward in powered HALO.

Figure 9 shows the movements of the center of gravity (CoG) in traveling direction for the upper body, the lower body and the whole body, which were calculated from the time series of the floor reaction forces at legs and crutches. As the curves are similar between HALO and powered one, the larger sift of CoG is observed in the case of powered HALO; that is, the stride with powered HALO was longer than HALO.

Figure 10 shows the movements of CoG in lateral direction for the upper body, the lower body and the whole body. The COG variations of powered HALO are much smaller than ones of HALO; moreover, the difference between CoGs of the upper body and lower body is also much smaller for powered HALO. These differences come from the fact that the user tilts the body rightward to obtain toe clearance of the left swing-leg in the case of HALO; on the other hand, such tilting the body was not required for the case of powered HALO because of the ankle rotation by the actuator. These results reveal that a



(a) HALO



(b) Powered HALO

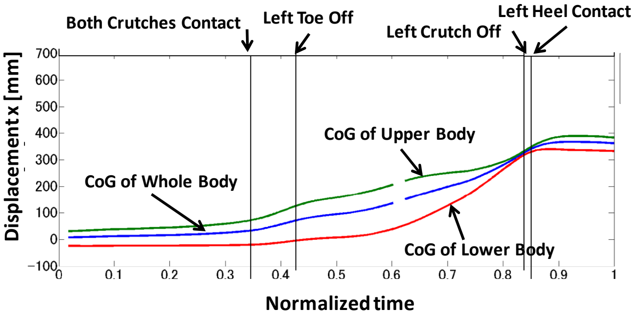
Fig. 8. Experimental results (stick figures).

certain magnitude of fluctuation of the upper body occurs with HALO while the smaller fluctuation occurs with powered HALO. This means that the proposed orthotic system with power assistive devices is able to achieve smoother movement for one step walk.

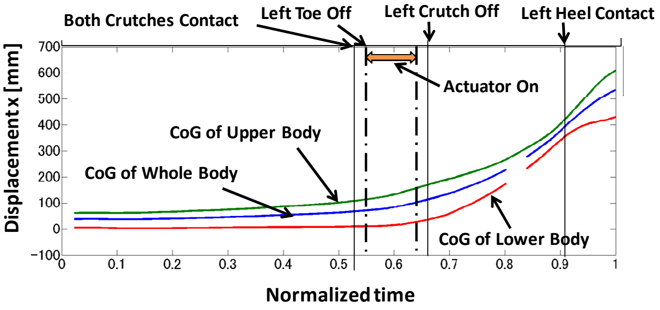
IV. DISCUSSIONS AND CONCLUSION

One of important problems to be solved is the safety with such assistive devices during walking. In the rehabilitation of spinal cord injury patients, exoskeleton robotic devices with weight bearing can assist the patient to walk on a treadmill. While treadmill training, the devices can provide the joint torques in the patient's lower limbs instead of physical therapists. Training system with an exoskeleton robotic device and a treadmill provides not only assistive joint torques but also a safety environment preventing from falling [11]. Although several kinds of powered orthoses have been proposed for paraplegics walking, the actuators attached at some joints of the exoskeletal orthosis can affect mainly on the movements of the body in the sagittal plane. In those orthoses, canes or crutches are usually required to stabilize the body movements because most of the powered orthoses are not able to stabilize the body in three dimensional space [12], [13]. We have proposed a practical method for stabilizing patient's walking with an exoskeletal powered orthosis in three dimensional space [14]. However, it is hard to solve the problems around stabilization with such powered orthoses because there exist many degree-of-freedom in the coupled patient-orthosis; moreover, the patient user has to control his body only with his workable muscles based on his insufficient sensory information. The situation of the users gives difficult problems around walking stability and controllability of active devices in the orthoses or exoskeletal robotic devices. We have to design a good human interface and the automatic control on the actuators for patient users to keep the stability of walking by controlling the actuators against several types of disturbances.

On the other hand, many types of hip-knee-ankle-foot orthoses including HGO and RGO have been developed, and those were put into the practical use, which achieve users' walking and the stability of posture with canes or crutches. No active device was used in those orthotic systems. However, most of those orthoses have not been successful because they are too bulky and difficult to use with wheelchairs. Compact types of orthoses have solved the problem of usability with the light weights and the easiness for the don/doff. If such compact orthoses can also solve the problem of the low energy efficiency for getting the moving distance, it will be ideal not only from the energy efficiency but also from the safety point of view. One of the authors tested on the energy efficiency of such orthoses: Para Walker, RGO, Walkabout, ARGO, Primewalk, and HALO. The efficiency of HALO was not best

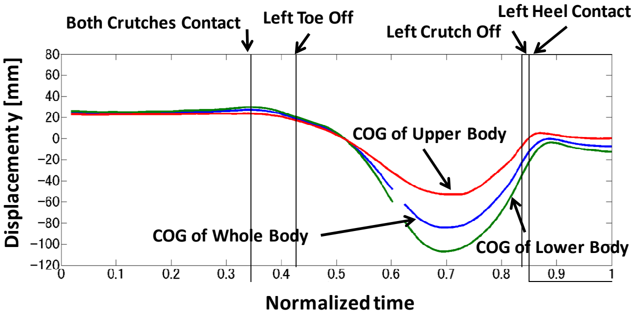


(a) HALO

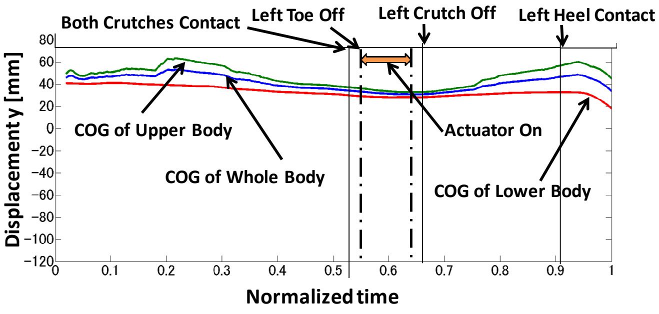


(b) Powered HALO

Fig. 9. Experimental results (CoG movements in traveling direction)



(a) HALO



(b) Powered HALO

Fig. 10. Experimental results (CoG movements in lateral direction)

but next to the best: Para Walker [9], [15], [16], [17]. Related problems of these orthoses to the energy efficiency are extraordinary gate patterns. For the examples, we frequently observe a big fluctuation of body orientation, too big pushing force with crutches, and a big pelvic rotation. One of the authors compared the pelvic rotations in the maximum angle variation from the neutral position with HALO and with other orthoses [8]. The pelvic rotation with Primewalk was around 50 degree and that of with HGO or RGO was reported to be 33 degree and about 25 degree, respectively [18]. The pelvic rotation of HALO, which was within 20 degree, was smaller than that of RGOs or HGO. We consider with these results that the main cause of pelvic rotation is the fixed ankle joints. The ankle joint motion of HALO gives stability in walking, and the mechanism provides the dorsiflexion moment of the ankle to assist the swing of the contralateral leg. As a result, the leg is so easily swung that any assistance by pelvic rotation is not required. From these reasons, the gaits with HALO become more natural than with other conventional orthoses. However, we understand that there are two weaknesses in HALO; it is not energy efficient and a big fluctuation of body CoG occurs (See Figure 10(a)).

This paper proposes a trial that can solve the problems of energy efficiency and posture stability by introducing minimum number of actuators into HALO. The increased weight with introducing the active devices was 3 kg. A simple trajectory was used for rotating ankle joints by the actuators. Although the experiments described in this paper were preliminary ones with three healthy subjects, it is shown that big fluctuations with HALO can be reduced by introducing actuators for controlling ankle joints (See Figure 10 (b)). In other words, we can achieve smoother movements and stability of user's posture in gates with powered HALO. It can be expected that the energy efficiency of gates with powered HALO becomes much better than HALO because of the smaller fluctuations of body CoG.

The mechanism of HALO is applicable to hip-knee-ankle-foot orthotic systems that have lateral hip joints such as HGO and RGOs by linking the ankle joint with the contralateral hip joint. More precious experiments with subjects: patients with spinal cord injury will be required for evaluating the energy efficiency and the postural stability while walking with powered HALO.

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