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Development of Single Leg Version of HAL for Hemiplegia

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Abstract— **Our goal is to try to enhance the QoL of persons with hemiplegia by the mean of an active motion support system based on the HAL's technology.The HAL (Hybrid Assistive Limb) in its standard version is an exoskeleton-based robot suit to support and enhance the human motor functions. The purpose of the research presented in this paper is the development of a new version of the HAL to be used as an assistive device providing walking motion support to persons with hemiplegia. It includes the realization of the single leg version of the HAL and the redesign of the original HAL's Autonomous Controller to execute human-like walking motions in an autonomous way. Clinical trials were conducted in order to assess the effectiveness of the developed system. The first stage of the trials described in this paper involved the participation of one hemiplegic patient who has difficulties to flex his right knee. As a result, the knee flexion support for walking provided by the HAL appeared to improve the subject's walking (longer stride and faster steps). The first evaluation of the system with one subject showed promising results for the future developments.**

I. INTRODUCTION

In the field of assistive technologies, robotics have been widely applied, focusing mostly on the human motor functions. With wearable robots -designed to encapsulate a part or the whole body of the user- a higher degree of integration between the man and machine have been reached, allowing the robot to act directly on the human body. In the context of assistive technology, this type of robots appears to be used mainly for two purposes: rehabilitation and daily motion support of persons with motor disabilities[1].

Regarding daily motion support, wearable robots make it possible to support the impaired motion by creating external forces onto the paralyzed limb. The aim is to affect the impaired motion to make it as close as possible to the motion of an able bodied person. The main expected effect is the enhancement of the quality of life of persons with motor impairements. Common examples of wearable robots used for daily life support are active orthoses and active prostheses[2]-[6].

More recently, wearable robots appeared in applications related to Rehabilitation of persons with disabilities. For instance, physical therapists (PT) often need to repeat many times the same exercice with the patient. In the the case of rehabilitation of patients with lower impaired limbs, a treadmill can be used but the therapists need to move manually each leg of the patient in an alternate manner. This process usually requires two PT's, one at each side of the treadmill and is physically demanding for the PT. One of the consequence is the shortening of the exercise session. A solution to this issue is the use of lower extremity wearable robot for gait training, in association with a treadmill[7]-[10].

The research presented in this paper focuses on the daily life support, and more particularly to support the walking of persons with hemiplegia. One can find in the litterature examples of assistive devices designed to support the impaired motion of the foot-ankle joint. The purpose of such active devices is to enhance the function of the impaired ankle by the mean of actuators. However, references concerning similar devices operating at the level of the hip joint or knee joint are more difficult to find.

To palliate this limitation, we have developed the HAL (acronym for "Hyberid Assistive Limb") to support the ankle, the knee and hip joints[11],[12]. The HAL is a wearable robot designed for a wide range of applications, from welfare to heavy works support, and built in several versions (full body version and two legs version). Due of its exoskeleton characteristics it also has the "Robot Suit" appellation. So far, the investigations related to the HAL has been focused on the development of a two legs versions for walking support. The results shown a significant improvement of the gate of the incomplete spinal cord injured subject[12]. The work presented in this paper concerns the development of the single leg version of the HAL for persons with Hemiplegia. The purpose of this research is to develop a single leg version of the HAL to be used by patients with hemiplegia.

The section II describes the single leg version of the HAL. In section III the autonomous controller is presented, followed by the experiments conducted with a person with hemiplegia(section IV). The section V contains the experimental results, and section VI discusses the effectiveness of the HAL in the context of hemiplegia. The paper is clotured by a conclusion in section VII.

II. SINGLE LEG VERSION OF HAL

The HAL is basically composed of an exoskeleton, several power units, the main controller, setup units (to allow the user to adjust the HAL behaviour) and the sensing system (Fig. 1).

The exoskeleton of the HAL system is an articulated structure designed to support the mechanical functions of the human lower body. It consists of a frame and active joints, and is attached to the user's hips and legs using belts. The joints of the exoskeleton (hip, knee and ankle) has one DOF in the sagital plane. The required torques by the

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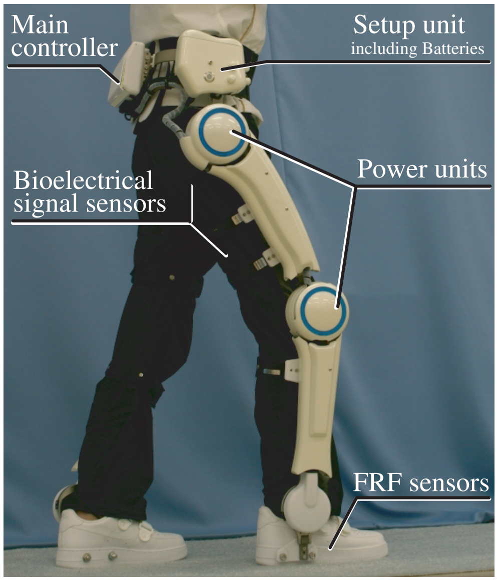

Fig. 1. Single Leg Version of the HAL

sytem's dynamics are generated by the power units. Each unit integrates an actuator, a motor driver, a microprocessor and a communication interface. The motion support is achieved by transmitting the torques of the power units to the user's legs through the exoskeleton frames.

The control of the HAL system is ensured by the main controller. Its purpose is to control and supervise the power units, monitor the batteries and communicate with the system operator. It modulates the assist torque of each power unit to perform motion support to walk, stand up and sit. Furthermore, it sends the sensors information and the system condition to the remote monitoring system, providing a visual feedback to the operator and allowing him to adjust the system parameters remotely.

The setup units contains an interface to adjust the parameters of the HAL and the batteries. The interface includes the HAL's power switch and the potentiometers to tune the assistive gain. This interface allows the wearer to turn on and off HAL easily and adjust the assist torque depending on the his/her physical condition or desired level of comfort.

The HAL is equipped with a sensing system based on several types of sensors to detect the HAL's state as well as the wearer's bioelectric signals. Potentiometers are mounted on each joint of the HAL and used as angular sensors to measure the joint angles. The bioelectrical sensors are attached on the skin surface of the extensor and the flexor muscles of the knee and the hip joint to detect their activity. Each shoe's insole contains two floor reaction force (FRF) sensors to measure the FRFs generated at the front and the rear of the foot (heel and ball areas).

III. Control Design

The HAL has a Cybernic Control System, based on a hybrid control algorithm, which consists of a Cybernic Voluntary Control (Bio-Cybernic Control) and a Cybernic Autonomous Control (Cybernic Robot Control).

Cybernic Voluntary Control provides a physical support according to the wearers voluntary muscles activity [13]. The power units of the HAL generates assistive torques by amplifying the wearers own joints torques. The joints torques are estimated from the wearer's bioelectrical signals, which are detected from the surface of the muscles. The wearer's bioelectrical signals are used as input command to control the HAL according to the wearer's intentions to move.

However, when the measured motion control signals include strong components of involuntary signals, the Cybernic Voluntary Control might not be suitable, like for instance in some cases of patients suffering from stroke related paralysis. In such case, the Cybernic Autonomous Control would be more adapted to provide an efficient physical support. The Cybernic Autonomous Control provides a predefined functional motion based on recorded motions patterns from able bodied persons. In this case the possible involuntary signals have not influence on the physical support, as the Cybernic Autonomous Control does not use the wearer's bioelectric signals to generate the assistive torques.

The Cybernic Autonomous Control adopts the Phase Sequence method with Human motion characteristics, that enables the HAL to generate Human-like motions in an autonomous way[14]. By using this method it is possible to generate functional motions such as walking, standing, etc... by combining elementary motion sequences called Phases.

The phase sequencing is made according 3 stages: First, the functional motion of an able bodied person is recorded, then analyzed based on motion variables and the wearer's physiological data. Then, the reference motion patterns are divided into motion sequences or motion phases. This division is made according to the specific intended motion like for instance ”swing the leg” or ”lift the body”. The resulting phases are then stored into the HAL. Each phase is adjusted in duration and amplitude depending on the wearer's characteristics such as the body parameters or the medical condition. Finally, the Phases are combined together to obtain the whole motion to be executed by the HAL. As a consequence, the HAL allows the wearer to perform a functional motion such as walking, sitting, etc... in an autonomous way.

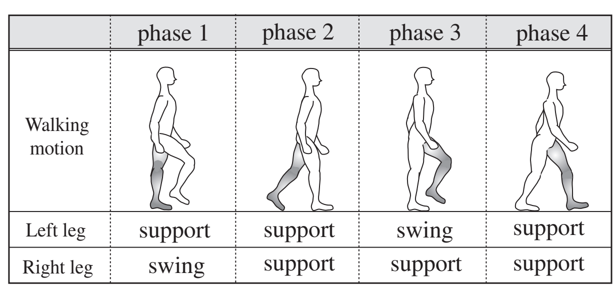

Fig. 2. Phase division in walking motion (The left leg is colored with gray.)

A. Phase division during walking

In this research the walking motion can be divided into four phases (Fig. 2). The phase 1 is the swing phase of the right leg. In this phase the left leg supports the body, while the right foot leaves the ground surface and the right leg swings forward. In the phase 2 the right foot contacts the ground surface so that the wearer's weight is supported by both legs. The weight is then completely transfered to the right foot. The phase 3 is the swing phase of the left leg. the left foot leaves the ground surface and the left leg swings forward. The body weight is fully supported by the right leg. The phase 4 is the the phase where the left foot contacts the ground surface and both legs support the body. The weight is then completely transfered to the left foot.

B. Realizing motion support in each Phase

The behavior of the HAL during the swing phase (the right leg motion in the phase 1 and the left leg motion in the Phase 3) is based on a PD controller, using the angle and angular velocity of the hip and knee joint (recorded from an able-bodied person during the same phase) as reference pattern. During this phase, the amplitude and the time interval of the reference angle and angular velocity are adjusted according to the user's physical parameters, physical condition and the desired level of comfort. During the support phase, the motion support is also based on a PD controller, but with a constant angle and a zero velocity as reference.

C. Phase shifting

Once the control has been made for each phase, the phase switching needs to be resolved. This is an important and delicate issue, as it should ensure a smooth transition between phases. For isntance, if the duration of the phase generated by the HAL differs from the duration of the required support, the HAL would provide an unnecessary load to the wearer that would put him/her in a dangerous situation, such as falling.

Current	Next	Shift index	Shift condition
phase 1	phase 2	*FRF_l_rear* *FRF_r_rear*	*FRF_l_rear* < *FRF_r_rear*
phase 2	phase 3	*FRF_l_total* *FRF_r_total*	*FRF_l_total* < *FRF_r_total*
phase 3	phase 4	*FRF_l_rear* *FRF_r_rear*	*FRF_l_rear* > *FRF_r_rear*
phase 4	phase 1	*FRF_l_total* *FRF_r_total*	*FRF_l_total* > *FRF_r_total*

Fig. 3. Phase shifting condition in walking support

The Phase shifting condition in walking support is shown in Fig. 3. The condition for the phase shifting from the swing phase to the double support phase (from phase 1 to the phase 2 and from phase 3 to phase 4) is defined based on the FRF value measured at the rear part of each foot. For instance during the phase 1, the FRF at the rear of the right foot (FRF_{r_rear}) increases while the FRF at the rear of the left foot (FRF_{l_rear}) decreases. The phase shifting occurs when FRF_{r_rear} becomes greater than than FRF_{l_rear}.

For the shifting from the double support phase to the phase related to the swing motion (from the phase 2 to the phase 3 and from the phase 4 to the phase 1), the condition which is considered is based on the summation of the FRF measured at the front and rear part of each foot. For instance during the phase 2, the summation of the FRF of the right foot (FRF_{r_total}) increases while the summation of the FRF of the left foot (FRF_{l_total}) decreases. The phase shifting occurs when FRF_{r_total} becomes greater than FRF_{l_total}.

IV. Experiment

The following chapter presents the experiments conducted to validate the single leg version of the HAL applied to hemiplegic user. The chapter introduces the user's characteristics, the detailed presentation HAL's structure, the HAL's controller, and finally the experiment protocol.

The subject is a 59 years old male with right hemiplegia, resulting from a stroke (Brunnstrom recovery stage IV). In his daily life, he wears an ankle orthosis, and walks using a cane. His walking is characterized by a circumduction gait, due to trouble to flex the right knee joint without flexing the right hip joint. He gave informed consent before participating.

Our goal is to use the HAL to support the flexing motion of the right knee joint of this patient. In order to achieve this,

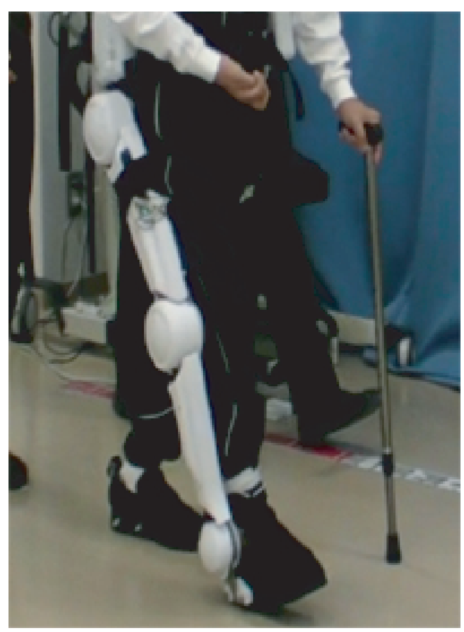

Fig. 4. Single leg version of the HAL fitted to the sujbect

we customized its Cybernic Autonomous Control to meet the patient's requirements. In order to fit the patient, we adjusted the length of the HAL's links according to the length of the patient's femoral and tibia. Each link of the HAL is contains two molded parts available in two sizes (L and M) and the brace (three). Fig. 4 shows the single leg version of the HAL fitted to the subject.

As the subject can move his hip joint by himself, the actuator of the hip joint was replaced by a free joint. Usually in the Cybernic Autonomous Control, an assistive torque is generated for the flexion and the extension during the swing phases. However, as the patient can voluntarily extend the knee of his right leg, the action of the Cybernic Autonomous Control is limited to the flexion.

The trials were organized in one hour sessions, which were performed once a week, during four weeks. In each session, the patient is asked to walk for a required distance (about five meters the two first sessions then longer until reaching ten meters). Each time the patient has covered the required distance, the HAL's parameters are then adjusted to improve the walking. The concerned parameters are the amplitude of the assistive torque, the timing of the phase switching and the motion velocity. To ensure the patient's safety, additionnal support was provided to the patient. During the two first sessions the patient used parallel bars then a cane once he got used to the HAL.

The evaluation of the walking support was made by comparing the data measured with and without using the HAL support. The comparison is based on the time to cover the required distance, the stride's length, the knee joint angle, the hip joint angle and the right foot FRF.

V. Results

Figure5 shows data recorded during one walking cycle. Those conventions apply to the measured data. The reference used for the joints angle is the value measured for the standing posture.The angles are considered positive during the flexion and negative during the extension. The assistive torque is positive during flexion and negative during extension. It appears that the HAL generates the assistive torque in the direction of the flexion and the knee flexion of the subject is performed during the right leg swing phase.

Figure 6 shows the knee joint angle and the hip joint angle with and without assistive support, during one walking cycle (strating when the right foot contacts the ground). It was clear that the right knee angle and the hip joint angle measured during the swing motion become larger when using the HAL.

The figure 7 presents the FRF measured on the front and back of right foot with and without the assist of HAL during one cycle of walking from contacting the right foot. When the subject is walking without the HAL, it appears from the FRF that the right foot contacts the floor with its whole surface simultaneously. Then the FRF remains almost constant while the weight shift forward. It means that the weight is not shifted smoothly from the rear to the front of the right foot. On the other hand, in case of the walking with the HAL, the FRF shows clearly that the foot contacts

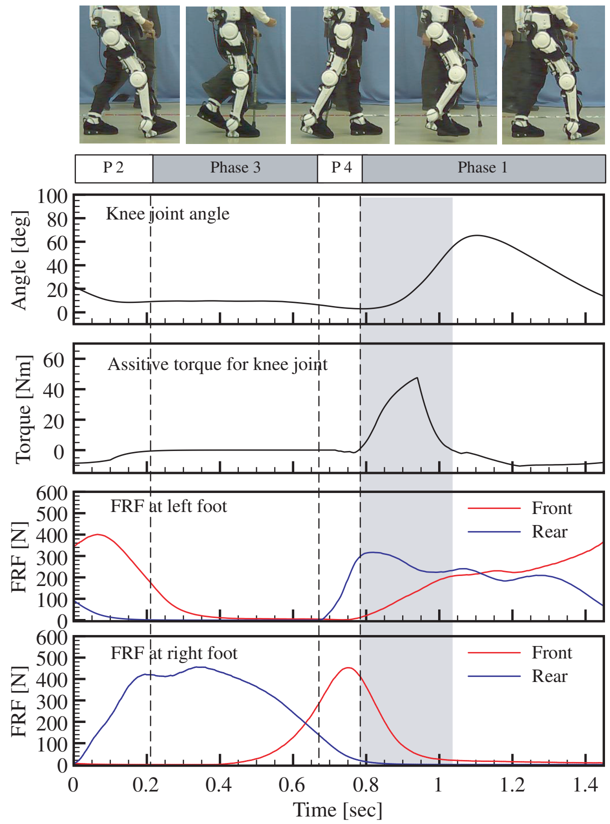

Fig. 5. Walking support with the HAL during one cycle

TABLE I

STRIDE LENGTH AND WALKING TIME WITH AND WITHOUT THE HAL

	Without HAL	With HAL
Left stride length [cm]	115	157
Right stride length [cm]	118	171
Walking time (10 m)[sec]	33.2	13.4

the ground from the rear first, then the weight is shifted smootly to the front. This phenomenon can be explained by the support of the active knee flexion which makes it faster and smoother to transfer the weight forward.

Table I shows the left and the right stride length and the walking time between ten meters with and without using the HAL. When the subject is wearing the HAL, the length of the right stride is longer and the walking speed is higher than whitout using the HAL.

VI. Discussion

The single leg version of the HAL was used to assess the support provided to a person with hemiplegia for the bending motion of his knee. The stride of the right leg increased more than significantly, due to a wider motion of the knee joint and the hip joint during the swing phase. Furthermore, the use of the HAL allowed to reduce the walking time because the HAL allows shift forward. Therefore we confirmed that

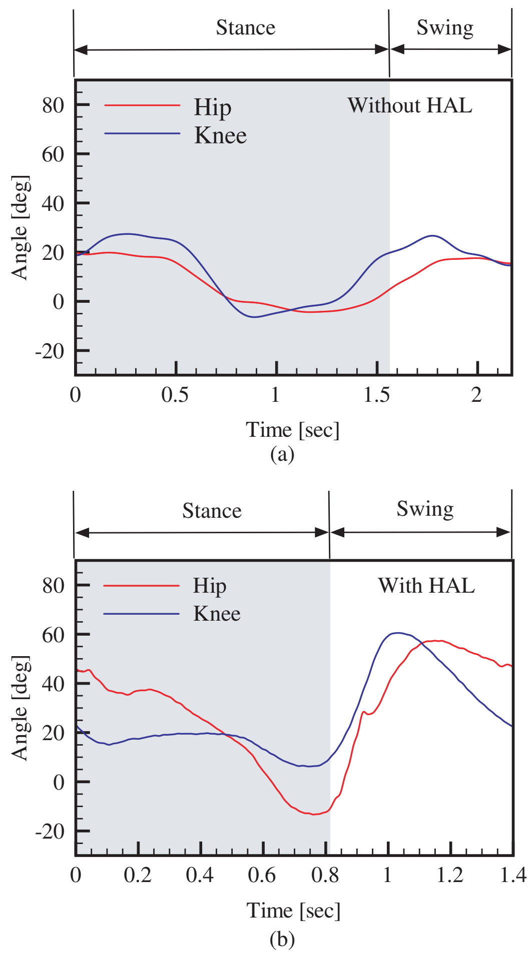

Fig. 6. The angles of knee joint and hip joint of the right side without the HAL (a) and with the HAL (b) during walking

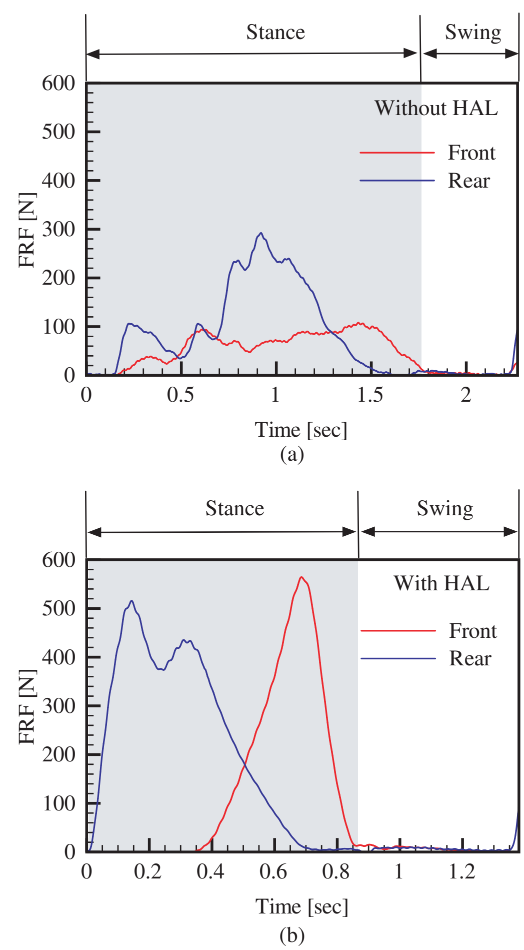

Fig. 7. The FRF on the front and the rear part of the right food without the HAL (a) and with the HAL (b) during walking

the single leg version of the HAL could improved efficiently the walking of the patient with hemiplegia. However, the use of HAL also increased the differential stride between the left and right leg (14 cm with the HAL and 3 cm without the HAL). This is a drawback as it emphazises the unsymetry between the left and right side. and make the gait more unnatural. This issue will be investigated in order to reduce this effect.

Ankle foot orthosis (AFO) have been commonly used by persons with hemiplegia. A standard AFO supports the motion of the ankle joint by using the elastic force generated in reaction to its deformation. Unfortunately this passive process does not allow to move paralyzed joints. In the case of the HAL, it supports actively the wearer's joints and compensates the motion limitations due to paralysis. By doing so, the single leg version of the HAL appears so far to be useable as an assistive device for hemiplegia.

Our final goal is to apply the HAL support to enhance the QoL of persons with hemiplegia.Although the first results seem to be promising, there are still two points which need to be investigated before the HAL can be used by persons with hemiplegia in practical situations. The first point concerns the weight of the HAL itself. In this paper, each test was conducted over a total distance of sixteen meters. After each trial the subject was asked about his impressions during the trial. Regarding the weight, the subject mentionned that he felt like the HAL had no influence on his walking. However, the HAL represents an additional load of 7 kilograms for the wearer, which is expected to be an issue when the wearer needs to walk for long distances. This point will be investigated more troughfully and one priority of the ongoing developments is the weight reduction by using lighter materials and smaller components.

The second point is related to the fitting system that should be made more simple to allow the user to put on and off the HAL more quickly and with less efforts.

VII. CONCLUSIONS

In this research, the HAL robot suit was adapted into a single leg version to support the walking of persons with hemiplegia. In order to move the paralized leg of the wearer, the Autonomous Controller initially implemented in the standard version of the HAL was redesigned. To investigate the efficiency of the system, the walking support was assessed with one hemiplegic subject who is not able to bend his right knee. As a result, the single leg version of the HAL allowed the subject to bend his knee properly, which improved the walking significantly, making it much more natural. To validate the results of this research on a wider range of users, the next developments concern the involvement of a population of subjects showing different types of hemiplegia. Finally, in order to use the HAL in daily life support, another direction of development is the reduction of the HAL's weight and the improvement of the fitting system.

VIII. ACKNOWLEDGMENTS

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