Development of an Assist Controller with Robot Suit HAL for Hemiplegic Patients Using Motion Data on the Unaffected Side

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***Abstract*— Among several characteristics seen in gait of hemiplegic patients after stroke, symmetry is known to be an indicator of the degree of impairment of walking ability. This paper proposes a control method for a wearable type lower limb motion assist robot to realize spontaneous symmetric gait for these individuals. This control method stores the motion of the unaffected limb during swing and then provides motion support on the affected limb during the subsequent swing using the stored pattern to realize symmetric gait based on spontaneous limb swing. This method is implemented on the robot suit HAL (Hybrid Assistive Limbs). Clinical tests were conducted in order to assess the feasibility of the control method. Our case study involved participation of one chronic stroke patient who was not able to flex his right knee. As a result, the walking support for hemiplegic leg provided by the HAL improved the subject's gait symmetry. The feasibility study showed promising basis for the future clinical study.**

I. INTRODUCTION

In individuals with hemiplegia after stroke, walking ability is impaired. Since walking is one of the major daily physical activity, it leads to lowered activity of daily living (ADL). Walking of individuals with hemiplegia is characterized by slower speed, instability and gait asymmetry [1]. While these properties are inter-related, gait asymmetry is considered to be the key indicator to evaluate gait quality [2], being correlated with challenges in balance control, gait inefficiencies, musculoskeletal degeneration, and hence decreased daily activities. It is also known that it worsens through time [3].

Gait asymmetry arises from impaired control in the affected limb [4], especially from difficulty in knee flexion and ankle dorsi-flexion [5], [6]. These difficulties result in compensatory motions in gait; circumduction of the affected limb during swing to prevent the toe from dragging on the ground [7], excessive plantarflexion of the unaffected ankle during stance[8], and excessive extension of the knee on the affected limb during stance to prevent sudden knee loosening and to attain stability [9].

Methods to improve gait symmetry have been investigated in the fields of physical therapy and rehabilitation robotics. However, there have been no methods which make possible for the patients to realize symmetrical gait in independent free walking. Conventional training on treadmill provided by a physical therapist manually guiding the affected limb does not assure enough accuracy for the gait to be symmetric, which is also the case in methods using visual or auditory biofeedback for guidance. As for robotic devices, active AFO [10] which assists ankle function and a controller of Lokomat which extends motion of the affected limb while impeding motion of the unaffectfed limb [11] were shown to increase gait symmetry. However, the former does not directly assure symmetry of gait during training and it relys on the patient's hip and knee ability for its improvement. In the latter, the constrained pattern of the unaffected limb may be different from the original spontaneous pattern that is appropriate for his/her physical properties.

In this paper, we propose a control method of Robot Suit HAL (Hybrid Assistive Limb, Fig.1.Left) [12] to realize spontaneous symmetric gait in walking of individuals with hemiplegia. HAL consists of an exoskeletal structure to be attached on the lower limbs and the waist of the wearer, actuated joints on the hips and knees, and a sensor system to detect various information about the wearer. In our control method, the joint angle sequence of the unaffected limb during swing is recorded and used to generate the reference trajectory for the subsequent swing of the affected limb, so that the affected limb traces the pattern generated by the unaffected limb in the preceding step. By this way, the wearer can experience walking in a spontaneous pattern generated by the unaffected limb, while keeping gait symmetry at a higher accuracy. The proposed control method was implemented on the robot. Feasibility of the method was tested in a clinical trial with a person with hemiplegia after stroke (Fig.1.Right), where he walked in a symmetric gait pattern while wearing the robot.

II. METHODS

A. Robot Suit HAL

HAL is basically composed of an exoskeleton, several power units, the main controller, and the sensing system (Fig.1 Left). The exoskeleton is designed to support the mechanical functions of the human lower body. It is an articulated structure, consisting of a frame, active joints at the hips and knees, passive joints at the ankles. It is attached to the user's hips and legs using cuffs and belts. The joints of the exoskeleton (hip, knee and ankle) have one DOF for each in the sagital plane. The torques are generated by the

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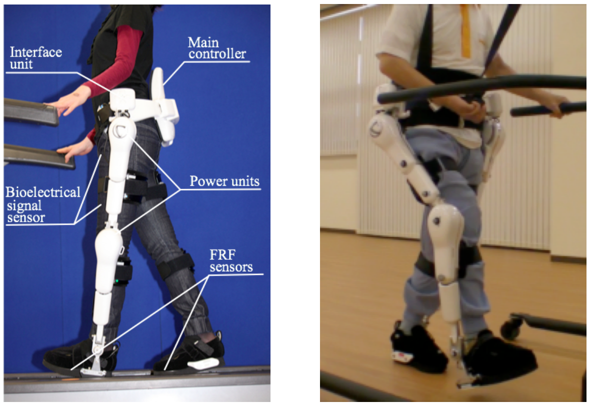


Fig. 1. (Left) Overview of Robot Suit HAL. (Right) A hemiplegic patient walking with HAL during the experiment.

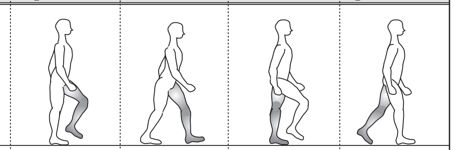
	phase 1	phase 2	phase 3	phase 4
Walking motion				
Left leg	swing	support	support	support
Right leg	support	support	swing	support

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

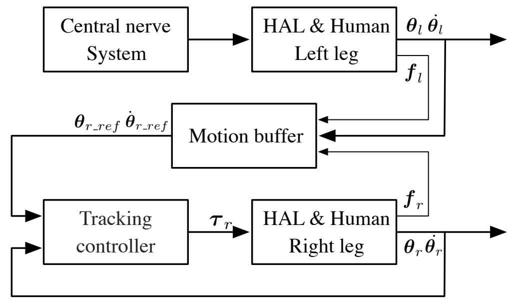


Fig. 3. Block diagram for HAL control system for hemiplegia patients.

power units at the hips and knees. Each power unit incorporates an actuator, a motor driver, a microprocessor and communication interface. The motion support is achieved by transmitting the torques from the power units to the user's legs through the exoskeleton frames.

The control of the HAL system is integrated by its main controller. It controls the power units for assistance and safety, gathering sensor data, detecting failures and communicating the sensor data to local computers to understand the wearer's and HAL's condition.

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 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).

B. Assist Controller

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

2) Control System: Figure 3 shows a control system to support hemiplegic leg motion on the right side (We suppose here the right side is the affected side). Through the all gait phases, the active joints on the unaffected side (left) are controlled to compensate viscosity, to allow spontaneous motion of the wearer. In the phase 1, while the wearer swings the left leg, HAL detects the angles $\boldsymbol{\theta}_l = [\theta_{lh}, \theta_{lk}]^T$ consisting of left hip joint angle θ_{lh} and left knee joint angle θ_{lk}, and calculates angular velocities $\dot{\boldsymbol{\theta}}_l = [\dot{\theta}_{lh}, \dot{\theta}_{lk}]^T$ consisting of left hip joint angular velocity $\dot{\theta}_{lh}$ and left knee joint angular velocity $\dot{\theta}_{lk}$. The $\boldsymbol{\theta}_l$ and $\dot{\boldsymbol{\theta}}_l$ are recorded in motion buffer and transformed into reference joint angles $\boldsymbol{\theta}_{r\_ref}$ and the reference angular velocities $\dot{\boldsymbol{\theta}}_{r\_ref}$, which are used for motion support in right leg.

As the walking phase transits to the phase 3, the tracking controller generates assistive torque on the right side $\boldsymbol{\tau}_r = [\tau_{rh}, \tau_{rk}]$ consisting of right hip joint torque τ_{rh} and left knee joint torque τ_{rk}, which are calculated using PD controller based on the differences between motion reference ($\boldsymbol{\theta}_{r\_ref}$, $\dot{\boldsymbol{\theta}}_{r\_ref}$) and the current right angles $\boldsymbol{\theta}_r = [\theta_{rh}, \theta_{rk}]^T$ consisting of right hip joint angle θ_{rh} and right knee joint angle θ_{rk}, and right joint angular velocities $\dot{\boldsymbol{\theta}}_r = [\dot{\theta}_{rh}, \dot{\theta}_{rk}]^T$ consisting of right hip joint angular velocity $\dot{\theta}_{rh}$ and right knee joint angular velocity $\dot{\theta}_{rk}$.

Detection of transition between the phases [13] is based on thresholding on the values of FRF sensors attached on the front and rear parts of the left and right feet.

C. Clinical Evaluation

We implemented a HAL with the proposed control method, and applied it to a 63 year old male patient with hemiplegia on the right side resulting from stroke. In his daily life, he wears an ankle foot orthosis, and walks using a cane. His walking is characterized by a circumduction gait, due to the difficulties to flex the right knee joint without

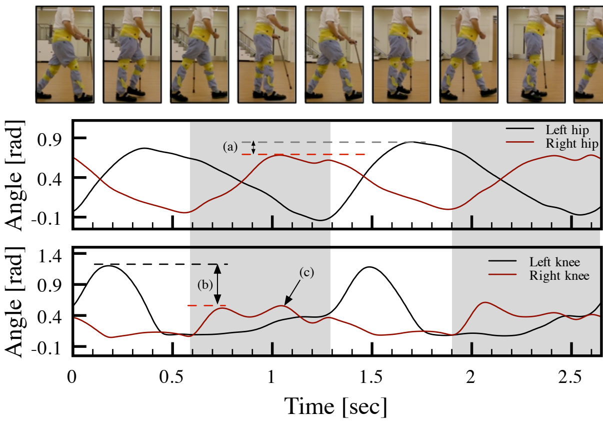


Fig. 4. Hip and knee joint angles of both legs for two gait cycles without HAL. The swing phase of right (affected) side is colored with gray.

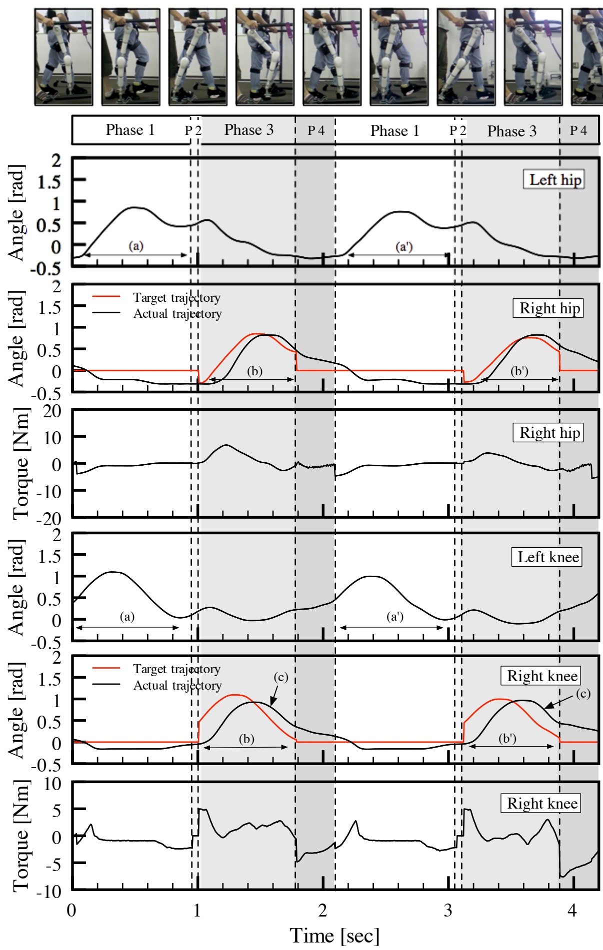


Fig. 5. Hip and knee joint angles of both legs for two gait cycles with HAL.

flexing the right hip joint. He gave an informed consent before participating.

The clinical trial was conducted once a week for four weeks, and each trial was 60 minutes. For the former two weeks, we mainly adjusted the parameters related to the detection of phase transition and the amount of the assistive torque based on report by the wearer and observation by the experimenters. For the latter two weeks, he learned to walk being aware of the integrated motion between HAL and his limbs with the fixed parameters. Figure 1(Right) shows the patient receiving the HAL's motion support.

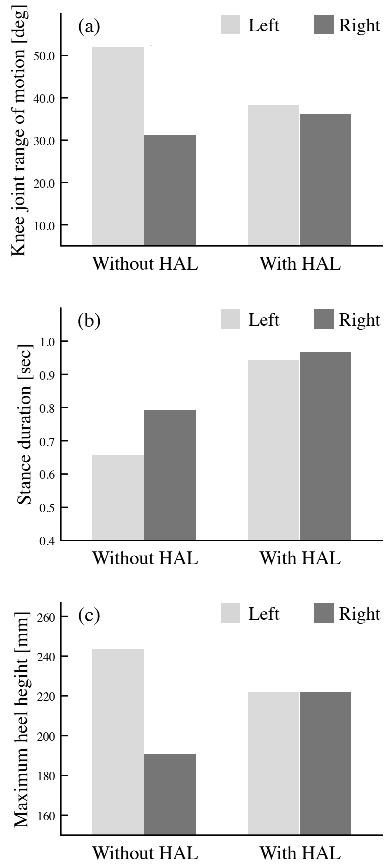


Fig. 6. Differences in the angle range for each knee joint in swing phase (a), support phase duration (b), maximum heel height in swing phase (c) with and without wearing HAL

We compared the angles of both left and right knee joints during walking with and without wearing HAL. Moreover, we also compared the difference between the motion range of the knee joint angle in swing phase, the support phase duration, and the maximum heel height from ground in swing phase. These data were calculated based on data measured by a motion capture system (VICON MX with 16 T40s cameras).

III. RESULTS

Hip and knee joint angles during walking without wearing the HAL are shown in Fig. 4. 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. It is clear that the ranges of flexion in the right (affected) side of the hip and knee joints during the swing phase are smaller than that in the left (unaffected) side (Fig. 4 (a), (b)), and especially there was the significant difference between both sides in the knee joint angles. The trajectory of knee joint angle during the swing phase was not generated smoothly (Fig. 4 (c)).

Figure 5 illustrates the joint angles and asssitive torques of hip and knee joints in affected side during walking wearing the HAL. The joint angle trajectories recorded during the swing phase in the left side (Fig. 5 (a), (a')) is used as target trajectories in the joint angle of the right side (Fig. 5 (b), (b') red). The assistive torque is positive during flexion and negative during extension. It was observed that the HAL generates the assistive torque during the swing phase of the right side based on the target trajectories, and the joint angles of the right side were provided in almost accordance with the target trajectories. The knee joint angle during the swing phase provided smooth trajectory (Fig. 5 (c)).

Figure 6 (a-c) shows the differences, by averaging data from 10 strides, in the angle range for each knee joint in swing phase, the support phase duration of each leg, and maximum heel height of each foot in swing phase with and without wearing the HAL. Walking without wearing HAL demonstrated differences between the right and left side. In particular, the knee joint range of motion and the maximum heel height of the right side were significantly shorter than those of the left side. The stance duration of the right side was longer than that of the left side. In contrast, walking with wearing HAL reduced the differences between the sides. The knee joint range of motion and the maximum heel length of the right side were significantly increased, while those of the left side were decreased. The difference of the stance duration was decreased while the stance duration of the left and right sides was increased.

IV. DISCUSSION

The clinical study was conducted with a hemiplegic patient who had asymmetric gait pattern in order to evaluate the feasibility of the proposed control method. The hip and knee joint angles on the affected side during the swing phase were quite similar to those on the unaffected side. Furthermore, the proposed control method reduced the variety of differences in gait between both sides due to hemiplegia. Therefore we confirmed that the proposed control method could provide the motion support to improve walking symmetry for the patient with hemiplegia. However, the knee joint range of motion and the maximum heel height on the unaffected side were decreased when the motion support was provided by the proposed control method. This may reflect the fact that the wearer has adjusted the unaffected gait according to the supported gait on the affected side. The next step would be to confirm the efficacy of the control method in the clinical study with several hemiplegic patients.

The control method is expected to contribute to functional recovery of gait for hemiplegic patients. It is based on the observation that the control method repeatedly provided the symmetrical motion support as locomotor treatment. In conventional rehabilitation, locomotor training tends to aim to walk as fast and stable as possible by exploiting the residual function in the unaffected leg, and does not prioritize the functional recovery to make the hemiplegic gait closer to symmetry. In contrast, by using the proposed control method, patients can learn symmetrical gait as far as they can keep standing posture and advance to the stage of locomotor training after stroke. In the near future, we will extend the clinical studies to examine gait functional recovery.

V. CONCLUSIONS

We proposed an assistive control method for hemiplegia patients to support motion of the affected leg using motion data of the unaffected leg during waking with HAL. It realizes symmetric gait based on the spontaneous swing pattern of the unaffected side. To investigate the efficiency of the control method, the walking support was applied in clinical trials with a hemiplegic subject whose gait was asymmetric. As a result, the control method allowed the subject to perform the motion of unaffected leg on the affected side, which improved the gait symmetry significantly. In the near future, we will apply this control method to subjects showing different types of hemiplegia.

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REFERENCES

[1] J. C. Wall and G. I. Turnbull, "Gait asymmetries in residual hemiplegia", Arch Phys Med Rehabil, vol.67 (8), 1986, pp.550-553.
[2] K. K. Patterson, W. H. Gage,D. Brooks, S. E. Black, W. E. McIlroy, "Evaluation of gait symmetry after stroke: A comparison of current methods and recommendations for standardization", Gait Posture, vol.31, 2010, pp.241-246.
[3] G. I. Turnbull and J. C. Wall, "Long-term changes in hemiplegic gait", Gait Posture, vol.3, 1995, pp.550-553.
[4] J. Perry and J. M. Burnfield, "Gait Analysis: Normal and Pathological Function (2nd ed.)", SLACK Incorporated, 2010.
[5] B. B. Bhakta, "Management of spasticity in stroke", British Medical Bulletin, vol.56 (2), 2000, pp.476-485.
[6] A. Thibaut, C. Chatelle1, E. Ziegler, MA. Bruno, S. Laureys, and O. Gosseries, "Spasticity after stroke: Physiology, assessment and treatment", Brain Injury, Vol. 27, No. 10, 2013, pp. 1093-1105.
[7] DC Kerrigan, EP Frates, S Rogan, "Hip hiking and circumduction: quantitative definitions", Am. J. Phys. Med. Rehabil., Vol. 79 (3), 2000, PP. 247-252.
[8] G. Chen ,C. Patten, D.H. Kothari, F. E. Zajac, " Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds", Gait Posture., Vol. 22 (1), 2005, PP. 51-56.
[9] SJ Olney, C Richards, "Hemiparetic gait following stroke. Part I: Characteristics", Gait Posture, Vol. 4 (2), 1996, PP. 136-148.
[10] J. A. Blaya and H. Herr, "Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait", IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol.12(1), 2004, pp.24-31.
[11] C. Bonnyaud, D. Pradon, J. Boudarham, J. Robertson, N. Vuillerme and N. Roche, "Effects of gait training using a robotic constraint (Lokomat) on gait kinematics and kinetics in chronic stroke patients", J. Rehabil. Med. Vol.46, 2014, pp.132-138.
[12] K. Suzuki, G. Mito, H, Kawamoto, Y.Hasegawa, Y. Sankai, "Intention-Based Walking Support for Paraplegia Patients with Robot Suit HAL", Advanced Robotics, vol. 21 (12), 2007, pp. 1441-1469.
[13] H. Kawamoto, T. Hayashi, T. Sakurai, K. Eguchi, Y. Sankai, "Development of single leg version of HAL for hemiplegia", Proc. of 31st Annu. Int. Conf. of the IEEE Engineering in Medicine and Biology Society, 2009, pp. 5038-5043.