HAL: Hybrid Assistive Limb based on Cybernics

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Abstract We aim to develop the Hybrid Assistive Lims (HAL) in order to enhance and upgrade the human capabilities based on the frontier science *Cybernics*. *Cybernics* is a new domain of interdisciplinary research centered on cybernetics, mechatronics, and informatics, and integrates neuroscience, robotics, systems engineering, information technology, "kansei" engineering, ergonomics, physiology, social science, law, ethics, management, economics etc. Robot Suit HAL is a cyborg type robot that can expand, augment and support physical capability. The robot suit HAL has two types of control systems such as "Cybernic Voluntary Control System" and "Cybernic Autonomous Control System". The application fields of HAL are medical welfare, heavy work support and entertainment etc. In this paper, the outline of HAL and some of the important algorithms and recent challenges are described.

Keywords: Robot suit, HAL, Hybrid Assistive Limb, Cybernics, Cybernoid, Cybernic Control, bioelectrical signal

INTRODUCTION

Humans and robots have limited capabilities. Cybernics would enhance and upgrade human capabilities. *Cybernics* is a new domain of interdisciplinary research centered on cybernetics, mechatronics, and informatics, and integrates neuroscience, robotics, systems engineering, information technology, "kansei" engineering, ergonomics, physiology, social science, law, ethics, management, economics etc. The research area will also cover the following fields which interact with the above domains of science.

- Cyborg studies
- Implantable devices (micro and nano- technology)

- Tissue engineering/Function replacement
- Neuroscience/Brain interface
- Kansei engineering/Ergonomics
- Medical welfare engineering
- Life support technology for elderly people (remote, in-home, hospital, institution, community medical welfare, vital-sensing)
- Robotics (life support, assistive technology, human support, middle-ware, fundamental technology)
- Human machine interface
- Ubiquitous computing/Sensing
- Secure database information technology
- Vital database construction technology
- Frontier medicine welfare network technology
- Creation of new industry (MOT, management, intellectual property management, law, economics)

HAL systems are classified in Cybernoid. Cybernoids are the enhanced human-machine hybrid systems based on Cybernics technologies. Robot suit HAL-5 (Fig.1) is one of the HAL systems, which consists of controller/computer, battery, bioelectrical sensors, angular sensors, acceleration sensors, floor reaction force sensors (COP/COG sensors), etc.

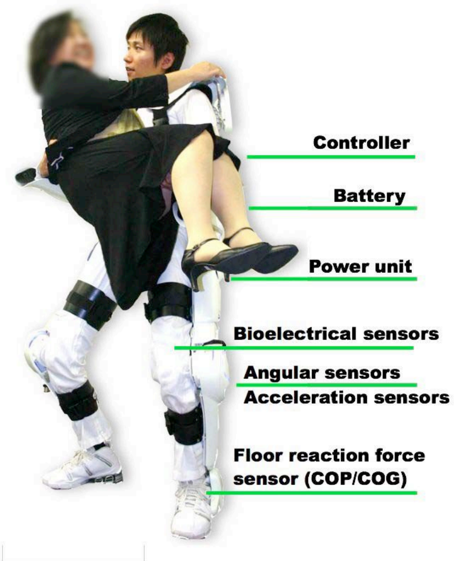
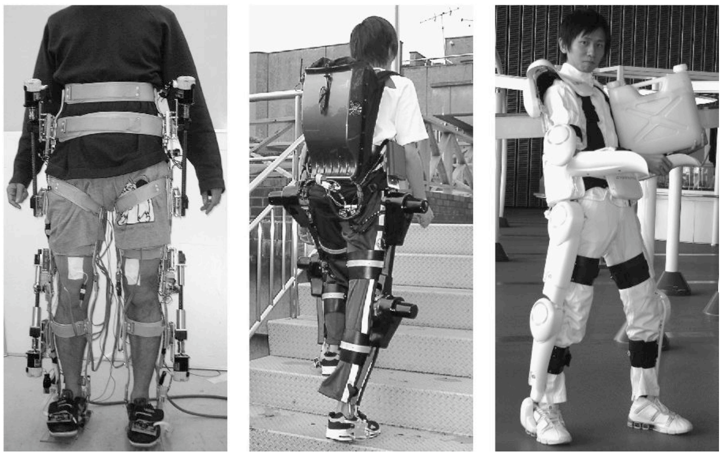


Fig. 1. HAL-5 (Type-B) Speficications: Height 1,600mm, Weight Full Body Type approx. 23kg(Lower body approx. 15kg), Battery Drive Charged battery(AC100V), Continuous operating time Approximately 2 hours 40 minutes, Motions Daily Activities(standing up from a chair, walking, climbing up and down stairs), Hold and lift heavy objescts up to 70kg, Hybrid Control System (Cybernic Control: Cybernic Voluntary Control, Cybernic Autonomous Control), Indoor and outdoor

In our study, a wearable-type robot ‘Robot Suit HAL’ (Hybrid Assistive Limb) has been developed in order to physically support a wearer’s daily activities and heavy work, since 1992. In the beginning of the project, fundamental research and one-leg version HAL studies were performed. Lower half version HAL-1, utilizing DC motors and ball screws as shown in Fig. 2a, was developed as the first lower half version prototype of HAL [1] and it enhanced the wearer’s walking ability by amplifying the wearer’s own joint torque. After developing some prototypes, HAL-3 (Fig. 2b) was developed toward a more suitable system to be used in actual daily life [2, 3]. These photos were photographed in those days as our memories. HAL would have so many application fields, such as medical and welfare, heavy work support, etc.



HAL-1 Type-B(1996-1999) HAL-3(1999-2003) HAL-5 Type-B(2005-)

Fig. 2. Historical challenges[4,5]: HAL series HAL-1, HAL-3, HAL5 after Prototype systems of Hybrid Assistive Limbs

Cybernic Control system

To provide effective physical support according to each wearer’s condition, it is necessary to strongly focus on the control algorithm as well as mechanisms of supporting devices. HAL has a cybernic control system that is a hybrid control system consisting of a ‘Cybernic Voluntary Control (Bio-Cybernic Control)’ and ‘Cybernic Autonomous Control (Cybernic Robot Control)’. The cybernic control system can provide suitable physical support to wearers in various conditions such as a healthy person, a physically challenged person, etc., by using the two types of algorithms as complementary controls. The features of each control algorithm are described below. The Cybernic Voluntary Control provides physical supports/actions according to the operator’s voluntary intention caused by the bioelectrical signals including muscle activity. The power units of HAL generate power assist torque by amplifying the wearer's own joint torque estimated from his/her bioelectrical signals, and the support motions are consequently controlled. This control was used for power assist of a healthy person's activities, e.g., walking and standing up from a sitting posture, and we confirmed the Cybernic Voluntary Control successfully supported a wearer's motion. Bioelectrical signals, including myoelectricity, are useful and reliable information to estimate a human's motion intentions because the signals are measured just before corresponding visible muscle activities. Thus, the wearer receives physical support directly by an unconscious interface using the bioelectrical signals, which much more easily realize operation than manual controllers such as a joystick.

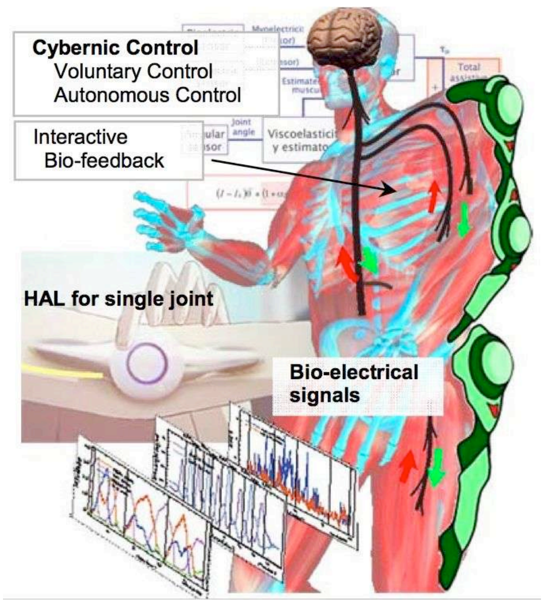


Fig. 3. Cybernic Control System: Cybernic Control system consists of Cybernic Voluntary Control system and Cybernic Autonomous Control System.

HAL can also physically support patients with some handicaps on their limbs as well as healthy people because HAL supports functional motions with multiple joints simultaneously, covering the whole of the lower limbs. However, as a whole, a patient with a gait disorder is not able to receive walking support by the Cybernic Voluntary Control because the signals that induce a broken walking pattern are not used for the power assist, and signals from the brain are not transmitted from the injured spinal cord to the more distant parts of the body and no signal is observed on the paralyzed muscles in the severest case. In that case, the Cybernic Autonomous Control can provide an effective physical support.

The Cybernic Autonomous Control autonomously provides a desired functional motion generated according to the wearer's body constitution, conditions and purposes of motion support. While bioelectrical signals are mainly used in the Cybernic Voluntary Control, various kinds of information apart from bioelectrical signals, such as reaction force and joint angle, can be used to provide comfortable physical support. It can be applied to rehabilitation and walking support for patients as well as power assist for healthy people, and it enables HAL to be used as alternate body functions for their handicaps or weakness of muscular power. In that case, HAL needs to observe a wearer's conditions and motion intentions from any motion information instead of his/her bioelectrical signals in order to provide a suitable support with a suitable moment. HAL-3 with the Cybernic Autonomous Control successfully enhances a healthy person's walking, stair-climbing, standing up from a sitting posture and cycling, synchronizing with his/her body condition [9]. In that work, floor reaction forces (FRFs) and joint angles are used as motion information to detect a wearer's conditions. Posture control, as well as sensing and recognition for an environment including a wearer are essential technologies for an entire autonomous physical support, but they remain to be solved.

Example for walking support by Cybernic Autonomous Control

In this chaper, the Cybernic Autonomous Control among the cybernic control systems is applied to HAL in order to support a paraplegia patient's walking[6]. Generally, the human intentions in his/her mind are essentially independent from the physical interactions between a body and an environment. As far as we know, no current technologies can directly measure and extract the human intentions. However, we can sometimes guess human intentions in their mind from their appearance or motion. In addition, we can estimate his/her intentions if we observe a motion or an appearance, which is closely connected with his/her intentions. A center of gravity (COG) shift to one leg is a prior motion to a walk. Some of the motions are indispensable to swinging a leg and can be observed earlier than a signal such as myoelectricity. The COG shift can be used for an early and smart trigger to start walking support, because the shift is involved in preliminary motions for a walk and a human does not have to operate any manual switch to start the walking support. On the other hand, gait stopping is similar to the time-reverse motion Walking support by Robot Suit HAL of the gait initiation and the COG stops at around the center of both supporting legs. Therefore, this paper proposes an intention estimator that can estimate his/her walking intentions from the COG shift that is closely connected with his/her intention.

In this paper, we define that intention-based support (including walking support) is to provide physical support for the wearer's next desired motion that can be predicted based on the current state or motion induced by his/her intention. In the case of walking, a human shifts the COG to a supporting leg side before he/she starts swinging a leg. If HAL can sense the COG shift induced by his/her intention, it can predict his/her walking start and then start walking support. Our project aims to realize comfortable walking support for paraplegia patients that reflect the patient's intentions on the start and stop of walking, cycle and stride of walking motion, walking direction, etc. We call the walking support conforming to these various intentions of walking 'intention-based walking support'. It is hoped that intention-based walking support improves the usability, safety and reliability of HAL. As the first step, we focuses on three kinds of intentions: the start and stop of walking and the beginning to swing a leg, and proposes a control algorithm that uses the patient's residual physical functions effectively. We need to observe not only the COG shift in the lateral plane, but also the forward COG shift and bending of the upper body in order to distinguish the gait initiation from other similar motions such as just stepping or changing a supporting leg for leg relaxation. However, HAL can estimate the patient's intention if we instruct the wearer to shift the COG to either of his/her legs in order to receive physical support for swinging a leg. Therefore, the FRF can be one type of reliable information that reflects his/her intentions without any manual interface if a patient can control his/her weight balance in the lateral plane by holding a walking frame with their own hands.

The purpose of this Cybernic Autonomous Control study for walking support is that HAL helps a patient with paraplegia walk in a standing posture. First, HAL should generate suitable bipedal walking according to the patient's body constitution. Reference trajectories for each joint support should be designed in a different way because bioelectrical signals are not observed from a patient with paraplegia. The reference motions consist of swinging the wearer's leg, supporting his/her weight and shifting his/her weight from one leg to the other. Second, HAL should provide walking support according to the patient's intentions that are estimated from the wearer's COG shift.

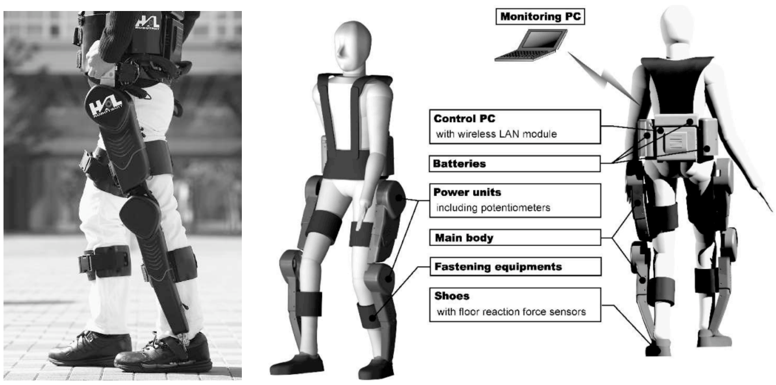


Fig. 4. HAL-5 Type-C for walking support of a paraplegia patient

In this experiment, HAL-5 clinical type (HAL-5 Type-C) made for participant A was used. Figure 4 shows an overview of HAL-5 Type-C. As in the case of the conventional type of HAL (HAL-3), HAL-5 Type-C consists of power units, exoskeletal frames, sensors and a controller. Power units are attached on each hip and knee joint, and actuate each joint by their torques. Springs are attached on the ankle joints so that the wearer's ankle joints could come back to a normal angle even if no external forces affect the joints. The spring action contributes to avoiding collisions between the toe of the swing leg and the floor. The exoskeletal frames are fixed to the wearer's legs with molded plastic bands and transmit the torques of the power units to his/her legs. There are angular sensors and FRF sensors to measure motion information of HAL-5 Type-C and a wearer to enable intention estimation for the wearer. Potentiometers as angular sensors are attached to each joint to measure the joint angles. FRF sensors utilizing a semiconductor-type pressure sensor are implemented in shoes.

Phase Sequence Method in Cybernic Autonomous Control

Walking motion in this application work should be considered to consist of three functions including swinging a leg, landing and supporting a body as shown in Fig. 5. In this paper, we call each span of three functions the swing phase, landing phase and support phase. In the swing phase, the patterns extracted from a healthy person's walk are applied as the reference patterns of the proportional and derivative (PD) control for the corresponding joints of a wearer. The reference patterns are used for the corresponding leg's control synchronizing with the wearer's intention estimated by our proposed algorithm. In the landing phase, we realize the leg function for a foot landing by not tracking reference patterns, but by applying constant-value control.

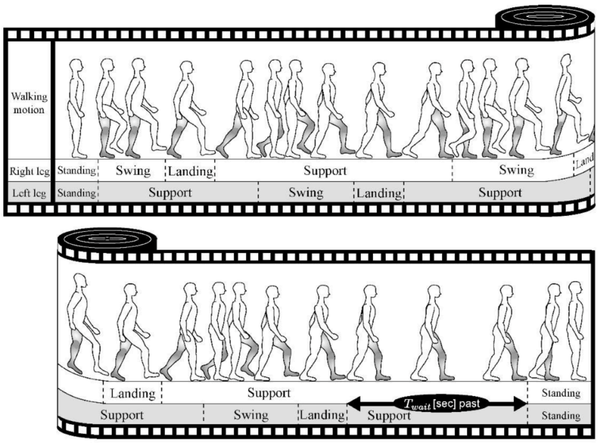


Fig. 5. Three functions in walking motion: swing phase, landing phase and support phase. T_{wait} is a temporal threshold to switch the walking support to the standing posture support. If a wearer wants to stop walking in their tracks, they just have to stop weight shifting for T_{wait} seconds.

We found that the knee joint of a wearer at landing is apt to be flexed by his/her own weight and much torque beyond the torque tolerance is needed to compensate for the knee bend. Therefore, the knee joint has to be extended earlier than the reference pattern by constant-value control. In the support phase as well as the landing phase, the leg is supported by constant value control in order to support the weight by one leg. Bipedal locomotion using a patient's legs is achieved by tracking control and by phase synchronization of motion support with the patient's intention. This control consists of the PD control using reference walking patterns based on a healthy person's walk. Figure 6 shows a block diagram for this tracking control and phase synchronization in Phase Sequence. The human intention estimator (HIE) in Fig. 6 has the FRF as input for the estimation algorithms. Three blocks under the HIE are a library of the reference patterns in the swing phase, and the reference values in the landing and support phase. The HIE allocates these references to the two legs during walking. There are six ordinary PD control blocks on the right side of the HIE and the library.

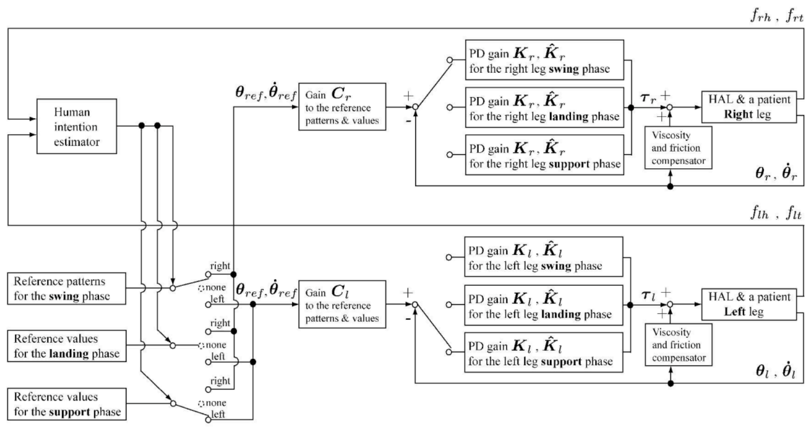


Fig. 6. Block diagram for tracking control and phase synchronization: The HIE has the FRF as input for the estimation algorithms described in the previous section. Three blocks under the intention estimator are a library of the reference patterns in three walking phases, and the reference values in the landing and support phase. The intention estimator allocates these references to the two legs during walking. The ordinary PD control blocks are shown on the right side of the intention estimator and the library.

The participant A is a 57-year-old male SCI (spinal cord injury) patient who has incomplete sensory and motor paralysis on the left leg, especially on the left lower thigh. He is diagnosed with an incomplete SCI; the sixth and seventh thoracic vertebra (T6 and T7) are damaged. His deep sensibility, including angle sensitivity, remains partially intact in his lower thigh; however, tactile, pain and temperature sensitivities are lost. Normally, he can walk quite slowly with limping by using two canes with both his hands. One of the experimental results is shown in Fig.7. His hip and knee joints follow the reference angles based on a healthy person's walk most of one cycle of the supported walk.

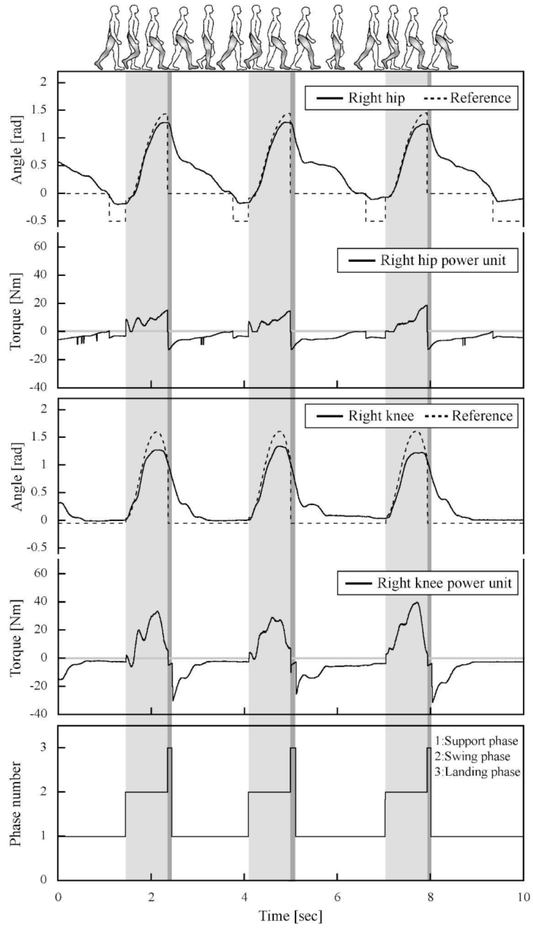


Fig. 7. Actual experiment (57-year-old male, SCI) Right leg joint angles with reference angles and power unit torques in each phase. His hip and knee joints follow the reference angles based on a healthy person's walk most of one cycle of the supported walk.

CONCLUSIONS

HAL systems and outline based on cybernics technologies are described in this paper. Especially, one of clinical applications for an actual paraplegic patient using cybernic autonomous control and the effectiveness of HAL are presented. HAL projects and cybernics projects have so many fused research aspects. Their project is already in its application stage, aiming their products to be used by society. In the Cybernics program, the interactive research between medicine and engineering allow an organic integration of Cybernics technology and regenerative medicine. We are confident that this research structure will accelerate both research and education in the unique field of physical function recovery and expansion, and that the Program will lead the development of this scientific frontier. The Program places the advancement of Cybernics as its central purpose. It has a promising potential in serving international as well as our future society. Breakthrough technology in the field of Cybernics will not be brought on by the fusion of man, machine and information technology alone. The inter-relations between medicine, engineering and humanity play an important role, and hence the Program incorporates consultations with ethics, legislation, security and human society from the early stage. We believe that such an integration of technology with humanities is an essential factor for the future development of Cybernics as well as for ensuring the utility of Cybernics for the society.

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References

[1] F. Ichihashi, Y. Sankai, S. Kuno, Development of Secure Data Management Server for e-Health Promotion System, International Journal of Sport and Health Science,Vol.4, pp. 617-627, 2006

[2] H. Toda, T. Kobayakawa, Y. Sankai, A multi-link system control strategy based biologilcal movement, Advanced Robotics, vol.20 no.6, pp. 661-679, 2006

[3] H. Toda, Y. Sankai: Three-dimensional link dynamics simulator base on N-single-particle movement, Advanced Robotics, vol. 19, no. 9, pp. 977-993, 2006

[4] H. Kawamoto, Y. Sankai: Power assist method based on phase sequence and muscle force condition for HAL, Advanced Robotics, vol.19, no.7, pp. 717-734, 2005

[5] S. Lee, Y. Sankai: Virtual Impedance Adjustment in Unconstrained Motion for Exoskeletal Robot Assisting Lower Limb, Advanced Robotics, vol.19, no.7, pp. 773-795, 2005

[6] K. Suzuki, G. Mito, H. Kawamoto, Y. Hasegawa and Y. Sankai: Intention-based walking support for paraplegia patients with Robot Suit HAL, Advanced Robotics, vol. 21, no. 12, pp. 1441 – 1469, 2007