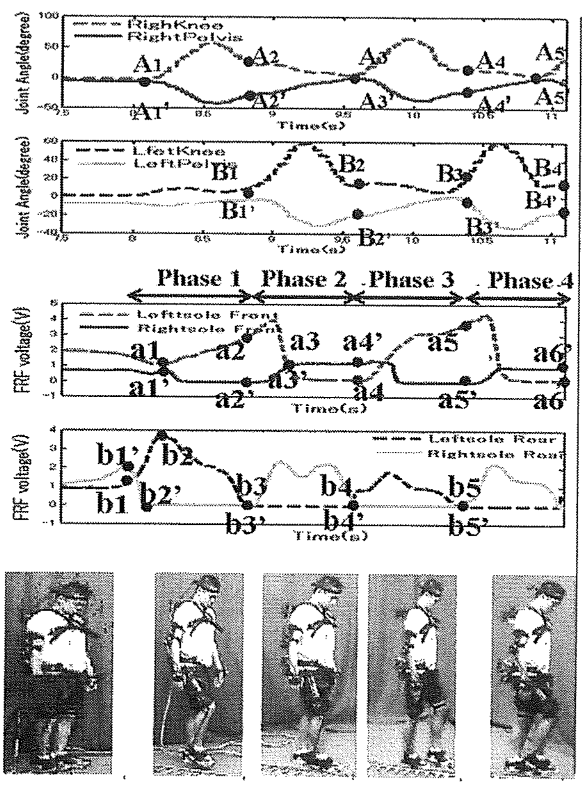


Fig 4. The walking by division of acquired data.

The joint angles, particularly those in the sagittal plane for the pelvis, knees, and ankles, were repeatable and readily. Therefore, human walking can be classified according to the four iterative Phases.

VI. A METHOD OF TASK GENERATION

The Task definition is relative with the objective of a set of motion trajectories that can be attained a desired position in space. Also, it is necessary to consider the capability of an operator to transfer these Tasks into the humanoid robot. In particular, the autonomous Tasks that can achieve work by following human motion patterns must be adaptable to the Phase composition method. Also, there must be flexibility in the transition between Phases in Task. Here, we describe the autonomous Task generation algorithm that can be transformed adopting constraint function from motion configuration and the third-order Bezier curve.

A. Trajectory Planning for Task

Many of biped robots are able to perform on surface conditions. In addition, their body have various foot motion patterns that fit within a human's actual conditions. It can be used to avoid obstacles and enhance manoeuvrability [11-12]. With trajectories planning, humanoid robot determines a suitable trajectory for moving before actually performing by interpolating. For example, trajectories are planned to obtain a specified target position, we can choose a set of constraints of its appropriate motion configuration.

B. Kinematic Transformation

To convert the joint angles into a trajectory, we consider a human's lower-limbs as a link having six degree-of-freedom (DOF), which can be established by constraints of motion configuration within each Phase, as shown in Figure 5. In sagittal plane, the angles are denoted by the he pelvis ($\theta 1, \theta 2, \theta 3$), knee ($\theta 4$) and ankle angle ($\theta 5, \theta 6$). The initial (*Pinitial*) and desired (*Pend*) positions give the COG of body that can be transformed from the end effector during walking. Hence, kinematics parameters is imposed by the initial and desired end position of COG in the x- and z- directions are defined in each Phase as

$$P_{initial} - P_{end} = Fi(\theta_i) \qquad (1)$$

Where, P_{initial} = [x_{initial}_pos, y_{initial}_pos, z_{initial}_pos, $\text{roll}_{\text{initial}}$, $\text{pitch}_{\text{initial}}$, $\text{yaw}_{\text{initial}}$] and P_{end} = [x_{end}_pos, y_{end}_pos, z_{end}_pos, roll_{end}, $\text{pitch}_{\text{end}}$, yaw_{end}] is initial and desired end position with respect to the waist coordinate, respectively. Also, $Fi(\theta i)$ denotes a constraint function of motion configuration on trajectory generation during the Phase. Using forward kinematics method, the COG trajectories of walking Task for humanoid robot is depicted in Figure 6(a). We introduce kinematic transformation to determine the Phase transition conditions for the Phase Sequences based on human joint angle data.

C. Adopting the Bezier curve

To illustrate the generating method of Task for humanoid robot, it would be dealt with end-effector based on acquired human's motion data that can be converted by constraint function after Phase division as mentioned above. As Task perfoming, it is necessary to interpolate from present position to next position that allow the humanoid robot to transfer more skilfully. The interpolation algorithm was adopted the third-order Bezier curve. We can choose suitable trajectories considering changeable environments with adjustment of control and anchor parameters in Bezier curve. Also, it is useful to plan smooth trajectories of end-effector with roundness type properties. In general, the parameters for a third-order Bezier curve can be given by $P = (P_0, P_1, \ldots, P_{n-1}, P_n)$. P_1 to P_{n-1} are the control points, which determine shape of curve while P_0 and P_n denote anchor points (one is the initial position, P_{initial} and the other is the desired end position, P_{end} in Phase). Hence, trajectory generation by the third-order Bezier curve consists of four points: two control and two position points. The control points are dependent on shape, which pull the curve vector in a direction. This equation is

$$X(t)=\sum_{i=0}^{n} B_{n,i}(t)P_i \qquad (i=0,\dots,n) \tag{2}$$

where,

$$B_{n,i}(t)=\frac{n!}{(n-i)!\,i!}t^i(1-t)^{n-i} \tag{3}$$

Eq. (3) describes the Bernstein polynomials, where t is an interval ranging from 0 to 1. The polynomials for a third-order Bezier curve are obtained by substituting n = 3. Substituting Eq. (3) into Eq. (2), $X(t)$ becomes

$$X(t)=(1-t)^3P_0+3t(1-t)^2P_1+3t^2(1-t)P_2+t^3P_3 \tag{4}$$

Here, vector Pi denotes the control points and anchor points of a third-order Bezier curve. This is dependent on determination the shape of curve for interpolation.

D. Walking Task

Figure 6(a) and (b) shows the period of double and single support Phases. One lower limb leaves the ground, while the other lower limb moves forward with a step stride. During the double support Phase, both lower limbs remain stationary. This Phase is planned using parameter adjustment of the third-order Bezier curve properly according to actual trajectories shape, which is determined from a function of motion configuration, $Fi(\theta i)$, in lower limbs on the sagittal plane.

The waist of humanoid robot moves along the z-axis according to the static transition of the lower-limb trajectories. In the course of Phase shifting, we assume that the landing sole remains parallel to the ground with zero velocity in order to avoid an impact. Moreover, the location of the COG of the robot must exist within an area given by,

$$x_{\min} \le x_{cog} \le x_{\max} \quad \text{and} \quad y_{\min} \le y_{cog} \le y_{\max}$$

where, the area of the sole is denoted by the coordinates ranging from $(x_{min},y_{min},0)$ to $(x_{max},y_{max},0)$ with respect to the ground.

E. Transition Recognition for the Phase Sequence

When a human walks, he/she can feel the reaction force that is distributed at the sole and note his/her posture innately. This applies to all Phases of walking: both when there is a single supporting lower limb and when both lower limbs are in contact with the ground. Since ground contact is a perceptual feature of motion, when one sole is in contact with the ground and the other sole is in a swinging state, a human knows the reaction force data to determine whether the timing of the transition to the next step is suitable. A comparison of foot trajectories between human's actual motion and Tasks for humanoid robot by adjustment of third-order Bezier curve parameter is shown in Figure 6(b).

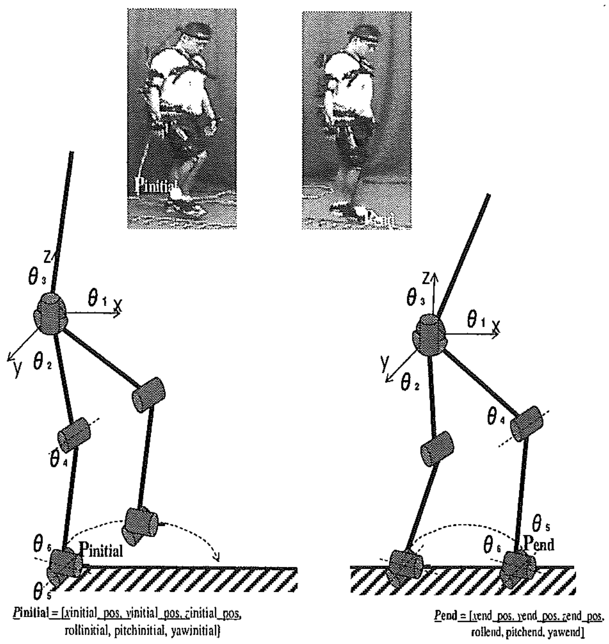
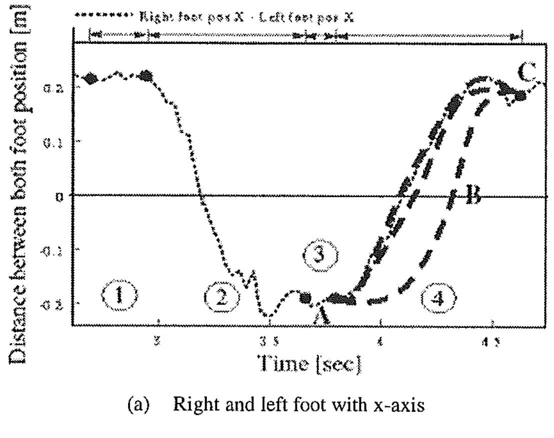


Fig. 5 Six-link model for walking by Phase division

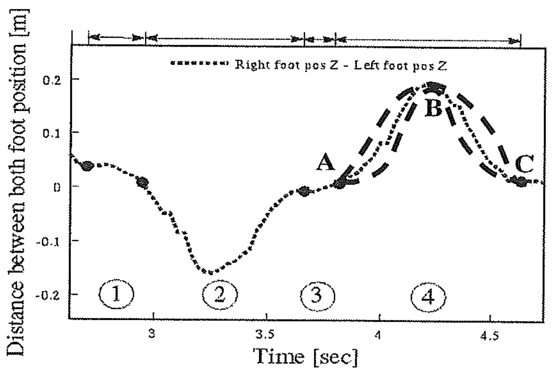
The FRF can determine index values to classify the Phases of the lower limbs for humanoid robot. There is a predetermined threshold of reaction that indicates ground contact. If the threshold satisfies the given condition, then ground contact is recognized and the Phase transitions shift to the desired next step while planning trajectory. In addition, configuration constraints from motion can be recognized to estimate an index value to determine whether a link structure and an environment are in contact by considering their relative position.

F. Phase Sequence for Tasks

The Phase Sequence is an operation that mimics human walking motion. Humanoid robots depend on linking the related Phases. In this operation, it is important that individual Phases are strongly connected to the actual Tasks.



(a) Right and left foot with x-axis



(b) Right and left foot with z-axis

Fig.6. Comparison illustration of walking data. Bold broken line means several possible trajectories by parameter adjustment of Bezier curve. Dotted is trajectory of actual human by kinematics transformation.

To realize this method, the Phase should contain information about the end-effector trajectories, in terms of the position and relative joint angle of the humanoid robot, from the point of origin through to the transition recognition indices, according to the motion strategy. The initial and ending position are designated by the third-order Bezier curve parameters (*P0, P1, ..., Pn-1, Pn*).

It depicts the trajectories that a humanoid robot should track. Moreover, transition period for the next Phase refers to a judgment condition using configuration constraints from motion and FRF thresholds in the present Phase conditions. If the conditions are satisfied by given threshold on each Phase, a handshaking operation between Phases occurs. Figure 7 shows a flow chart of all processes during Phase transition, where *N* and *i* are the number of Phases and Phase time interval, respectively. A good set of transitions for a Phase Sequence can be expressed as states.

STATE 1 (Initial): $Ph + i \le P_{0\_Phase1}$

The initial point of the Phase with position P_{0_Phase1} is at time *Ph* + *i*. The Task, which is generated by the trajectory, is can be planned in present Phase before the transition to the next Phase.

STATE 2 (Via): $P_{0\_Phase1} < P_{4\_Phase1}$

Trajectory for Task generation is described at this state through appropriate parameter adjustment of the third-order Bezier curve.

STATE 3 (Handshaking): $P_{4\_Phase1} \le P_{0\_Phase2} < Ph+i+1$

A Phase transition period, determined by the given threshold, is required over a desired time interval. Handshaking operation between desired end point of present Phase (*P4_Phase1*) and the initial point of the next Phase(*P0_Phase2*) occur.

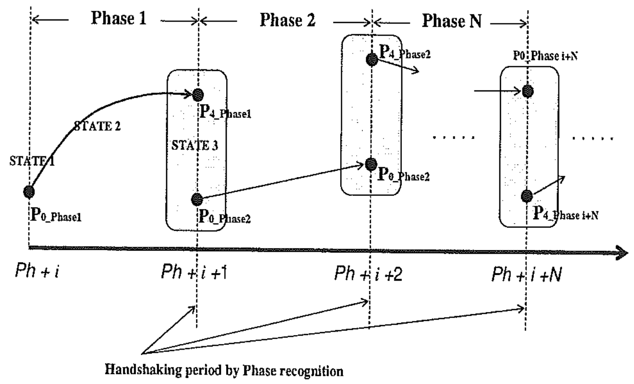
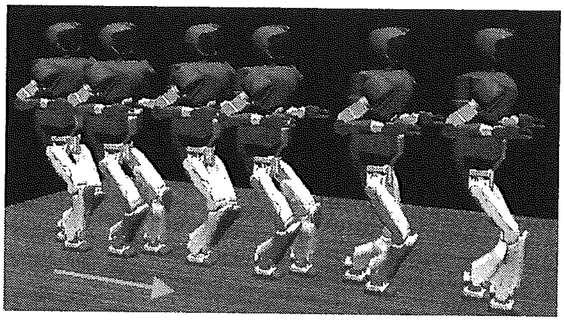


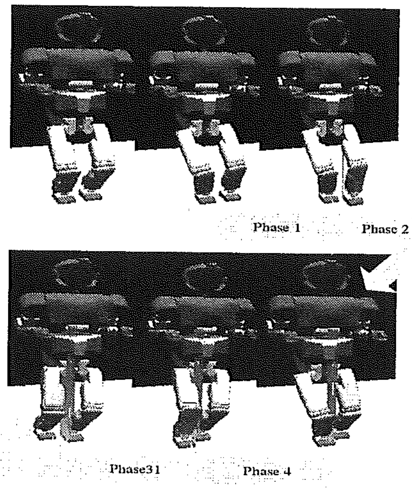
Fig.7. Schematic illustration of a good sequence for Phase transition

V. SIMULATION OF THE PHASE SEQUENCE

The walking motion was divided into four Phases based on both the contact of FRF and joint angle data. This division was chosen so that each motion contained both motion data and a threshold index. Figure 8 shows snapshots of the simulation results.



(a) The snapshot of humanoid robot walking



(b) Walking by Phase division

Fig.8.The simulation results of walking Task generation for humanoid robot according to Phase Sequence method.

VI. CONCLUSION

We proposed an algorithm that generates autonomous Tasks for a humanoid robot based on analysis of the human motion strategy for continuous Phase Sequence. We acquired sets of human motion data, consisting of walking. We then applied the third-order Bezier curve using kinematics transformation to adapt data into a humanoid robot. The motions were classified into several Phases. To determine an appropriate Phase transition procedure, it was necessary for the algorithm to recognize predetermined thresholds. As a consequence of using human motions as references and applying Phase Sequences, which consisted of a series of individual Phase, the walking Task for humanoid robot were generated. In the future, we expect to develop the algorithm further to include more various Task and its composition methods in order to perform in environments.

VII. REFERENCES

[1] Nancy S. Pollard, Jessica K. Hodgins, Marcia J. Riley, and Christopher G. Atkeson: "Adapting Human Motion for the Control of a Humanoid Robot", *Proc. of International Conference on Robotics & Automation (ICRA2002)*

[2] Christopher G. Atkeson, Joshua G. Hale, Frank Pollick, Marcia Riley, Shinya Kotosaka, Stefan schaal, Tomohoiro Shibata, Gaurav Tevatia, Ales Ude, Sethu Vijayakumar, and Mitsuo Kawato: "Using Humanoid Robots to Study Human Behavior", *IEEE Intelligent System 2000, pp.46-55.*

[3] Hiroyuki Miyamoto, and Mitsuo Kawato: "A tennis serve and upswing learning robot based on bi-directional theory", *Neural Networks 1998, pp.1331-pp.1344.*

[4] Okan Arikan, and D.A.Forsyth: "Interactive Motion Generation from Examples", *ACM SIGGRAPHIC 2002, Vol. 21, No.3, pp.483-pp.490.*

[5] Kenta Suzuki, Haruki Imai, Yuichiro Kawamura, and Yoshiyuki Sankai: "Gait Control of Humanoid on Irregular Terrain Considering Interaction with Environment", *Proc. of International Workshop on Robot and human Interactive Communication (ROMAN2003)*

[6] Yuichiro Kawamura, and Yoshiyuki Sankai: "Humanoid control method based on human knack for human care service", *Proc. of International Conference on System, Man and Cybernetics (SMC2002)*

[7] Seong-Hoon KIM, Haruki IMAI, and Yoshiyuki SANKAI: "Interactive Task generation for Humanoid Based on Human Motion strategy", *Proc. of International Workshop on Robot and Human Interactive Communication (ROMAN2004)*

[8] "http://www.metamotion.com"

[9] Suwoog Lee, Yoshiyuki Sankai: "Power Assist Control for Walking Aid by HAL Based on Phase Sequence and EMG", *Proc. Of International Conference on Control, Automation and Systems(ICCAS2001), pp.353-pp.357*

[10] Hiroaki Kawamoto, Shigehoro Kanbe, and Yoshiyuki Sankai: "Power Assist Method for HAL-3Estimating Operator's Intention Based on Motion Informtiont" *Proc. of International Workshop on Robot and Human Interactive Communication (ROMAN2003)*

[11] Bizzi E, Accornero N, Chapple W, and Hogan N: "Posture control and trajectory formation during arm movement", *J .Nerosci 1984, 4: pp.2738-pp.2744.*

[12] Qiang HUANG, Kenji KANEKO, Kazuhito YOKOI, Shunji KAJITA, Tetsuo KOTOKU, Noriho KOYACHI, Hirohiko ARAI, Nobuaki IMAMURA, Kiyoshi KOMORIYA, and Kazuo TANIE: "Balance Control a Biped Robot Combining Off-line Pattern with Real-time Modification", *Proc. of International Conference on Robotics & Automation, 2000 (ICRA2000). pp.3346-pp.3352*

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Stair Climbing Task of Humanoid Robot by Phase Composition and Phase Sequence

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***Abstract* – A goal of this work is to propose an algorithm that generates extended Task of humanoid robot to endure a large variety of performance. In this approach, it is likely that using "Task" library, which is constructed by previous Task is effective method to generate extended Task of humanoid robot according to environment change. It could be realized by method adopting "Phase" transition, defined as "Phase Sequence". Also, it would realize to plan a Task that required for humanoid robot in environment change using re-composition and re-using of constructed Phase without motion experiments and planning from scratch. We have been applied a previous Phase of step ascending and walking Task based on strategy of actual motion for humanoid robot Task, stair climbing. In the connection of two Tasks, we adopted third-order bezier curve, which can be transformed desired trajectory using modifying its control parameters. Furthermore, appropriate Task transition operation for Phase Sequence method was applied by re-composition of Phases as variation of designated environments. As a result, extended Task, stair climbing, was realized by recomposing of two fundamental Tasks. In conclusion, a proposed Task generation algorithm was verified.**

***Keywords* – Humanoid robot, Stair climbing, Motion composition, Phase Sequence.**

I. INTRODUCTION

Motion generation algorithm of humanoid robot is important theme. However, it is difficult to achieve desired motions, which is defined "Task", on humanoid robot performance due to complicated link structure of body. Although human body consists of multiple joint, he or she can execute numerous behaviors in various space conditions since it is capable of managing to capricious change by acquired empirical skill, which he learned for a long time. Normal human motion consists has many divided motion components. As using strategy above mentioned, if we could take advantage of this aspect for generating Task of humanoid robot, it would be an effective method because a Task can be decomposed by fundamental Task.

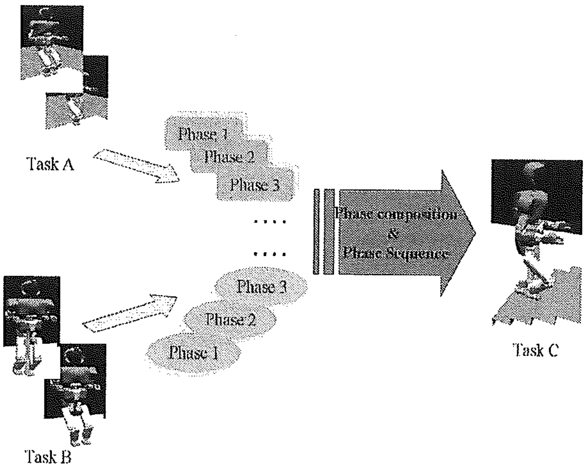

Fig.1.The overview of method for extended Task generation, such as stair climbing by Phase recomposition and Phase Sequence.

Some researches of humanoid robotics that generate motion have been explored [1-3]. These works mainly has been described motion planning of restricted situation of circumstance. However, it should be considered the algorithms that how can humanoid robot in human space, demanded for extended Task according to variable environments, realize generation.

To advantage of our approach is distinguished from above research. We develop the method that adapt to changing desired environments for human's behavior. A more and broadly useful approach would be exploited for appropriate Task generation of humanoid robot without actual motion experiments and Task planning according to variation environments from scratch.

This derived from concept that some Task is categorized into fundamental Tasks [4]. For example, stair climbing Task is composed by two Tasks, such as walking and ascending step as shown in figure 1. If the humanoid robot and real environmental conditions are the same as that of pre-planned motion, then it is can be taught by human behavior as following pattern. As for many humanoid robot has to modify a pre-planned

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program about motion generation according to changeable environments.

So, we propose the extended Task generation method by re-composition and Phase connection, which based on constructed actual capturing and transformed data of fundamental human motions in advance. This study was conducted as follows.

1. (1) Extended Task for stair climbing would be referred two Tasks, ascending step and walking based on transformed data from capturing system previously.
2. (2) These Tasks classified into smaller one or the other motion unit called "Phase".
3. (3) We define motion composition operation as "Phase Sequence", which was transformed into a humanoid robot using three-order bezier curve by transferring of designated position of Task in environments.
4. (4) To generate extended Task, Phase can be recomposed by parameter modification of bezier curve, and connected by Phase Sequence.

In our study, we show that validity of extended Task generation, such as stair climbing, using recomposition of preparing Task in library and Phase Sequence.

II. MOTION ANALYSIS

The humanoid robot consists of rigid links that are connected to several revolute joints, which permit relative motion of neighboring link structure. Since, the type of performance by the form of contact with the ground, a transition movement in humanoid robot would be restricted within joint angle and kinematics configuration. However, it is difficult to define a motion patterns. Toward this problem, the motion to determine the humanoid robot motion based on analysis of human motion was considered. Such a technique also has the advantage to generating Task that adapt to environments or condition for a humanoid robot. The development method is described by the posture of actual humans.

A. Phase and Phase Sequence

A behavior of human indicates that there are as almost endless variety of means. In this paper, when the fundamental motion characteristics of all theses kinds are considered as shown Figure2. Motions can be classified as essentially one or the other, or a combination of individuals. So the step in ours analysis, we classified into smaller fundamental motion unit "Phase" which contain the information that investigated turning point and desired position by trajectory planning based on extracted data from human.

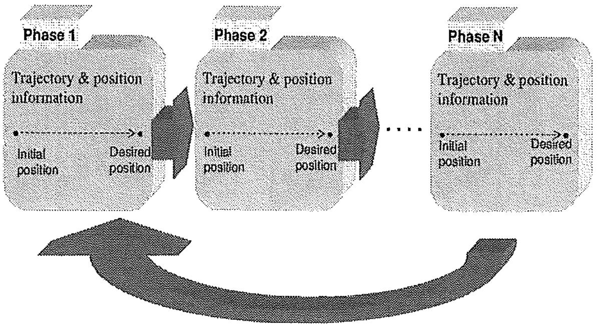


Fig.2.Exemple of performable Task by Phase and Phase Sequence

The classified Phases were linked to each other with order for generating the objective Task. We define what this is "Phase Sequence" method for application, which is were made since then [4,5]. A motion composed of related Phase was define as "Task".

B. One step ascending Task

Figure 3 shows the snapshot of actual human motion and step ascending Task of humanoid robot, which is consists of fundamental four Phases individually. Also, this trajectory result of Task is described as figure 4.

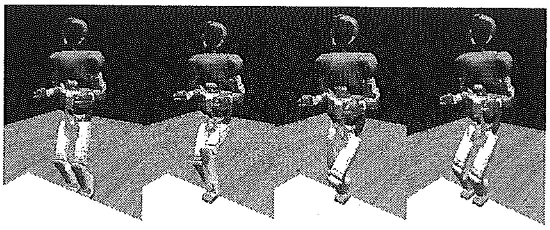
-Phase 1 can be defined the initial period of ascending Task for humanoid robot from a stationary posture to the start ② of the COG(Center of Gravity).

-Phase 2 describe left leg swinging and it move from ground to the above footpace according to desired trajectory in figure 4(d), which is determined by extracted data from actual human motion.

-Phase 3 is period of the COG movements and contact with on stair. The body of humanoid robot is bent forward to area ③ ascending to COG trajectory in order to maintain stable posture ④. It is state of ready shift the next Phase.

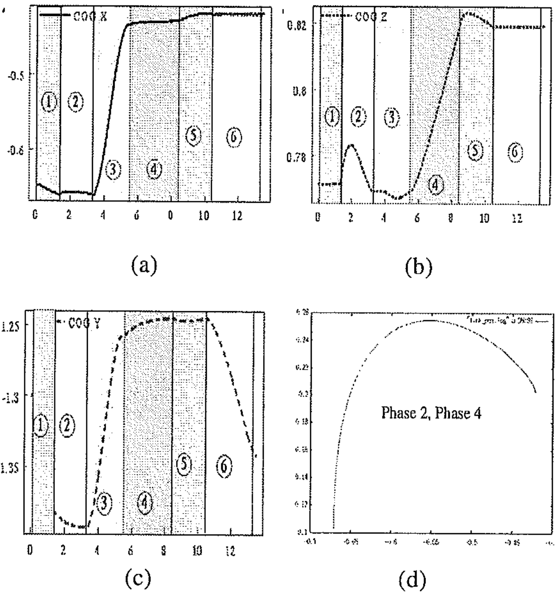
-Phase 4 is the final Phase of Task. This Task can be considered the period that is starting of the right leg swing motion occur in order to ascend according to desired trajectories of right leg in figure 4(d), similar to Phase 2. In this Phase, COG return to initial posture ⑤ ⑥ and step ascending Task is stop.

(a) Human step ascending



(b) The Task of step ascending for humanoid robot

Fig.3 The snapshot of human and humanoid robot step ascending Task



(a) (b)

(c) (d)

Fig.4 The prepared trajectory of step ascending Task for humanoid robot

C. *Walking Task*

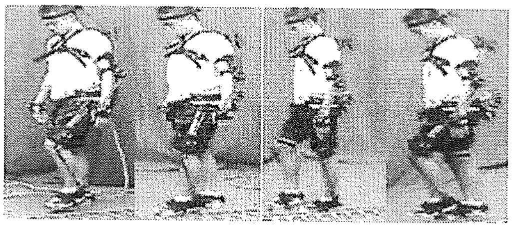
Figure 5 shows the snapshot of actual human motion and humanoid robot walking Task, which is compose of iterative fundamental four Phases preparing trajectory results shown as figure 6.

-Phase 1 describes the period of beginning from a stationary position on double foot for stability to the starting of the swing leg motion. Because the lower-limb starts to move forward, a new Phase in which the lower-limb is in front of the forwarding-moving COG.

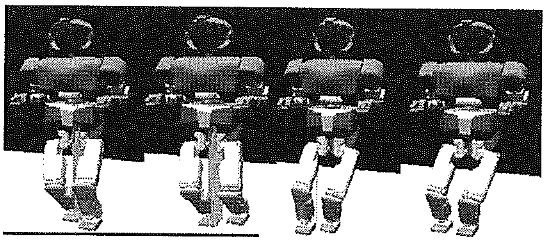
-Phase 2 is the period of motion extending from swing of leg to supporting the upper body with both legs. The left lower-limb is in contact with the ground while transferring forward of COG, and the left leg is propelled forward to the desired lift-off position. Moreover, we can determine the length of stride according to parameter adjusting of third-order bezier curve.

-Phase 3 is definition period that stance occurs between Phase 2, and the starting of the left lower-limb swing, similar to Phase 1.

-Phase 4 is final Phase in the walking Task. The COG transfer moves forward from supporting leg to single leg, which examined as Phase 2. The end of this Phase is the returning position for Phase 1.

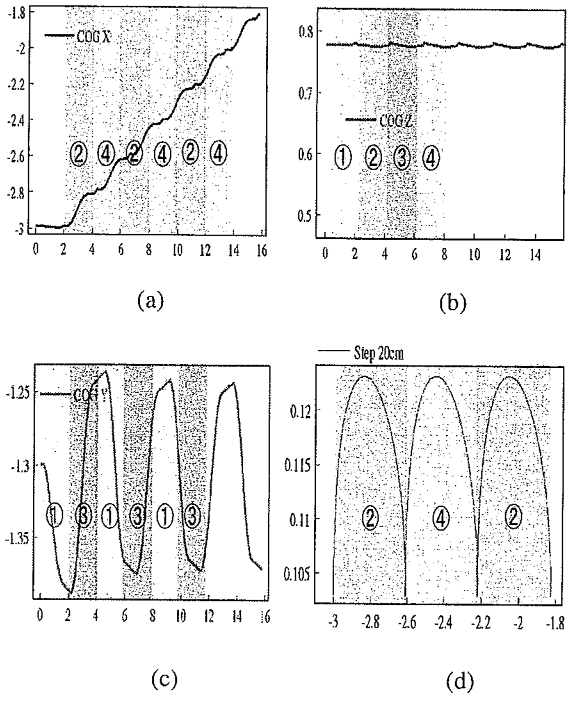


(a) Human walking



(b) The Task of walking for humanoid robot

Fig.5 The snapshot of human and humanoid robot walking Task



(a) (b)

(c) (d)

Fig.6.The prepared trajectory of walking Task for humanoid robot

III. A METHOD OF TASK GENERATION

The Task definition is associated with the objective motion set of trajectories, which realize work or attain a desired position in environments. It is necessary to consider the capability of an operator to transfer these Tasks into the humanoid robot using real environment variables. In particular, the autonomous Tasks that can be used to achieve work by following human motion patterns must be adaptable to the Phase composition method, and there must be flexibility in the transition between Phases. In order to obtain a Phase Sequence from a set of Phase transitions, a method of planning the desired trajectories using kinematics transformation from motion configuration, bezier curves, and transition recognition is required.

A. *Trajectory planning for Task*

Many of biped robots are able to perform on condition such as stair, irregular terrains and standing-up. In addition, their lower-limbs have various foot motion patterns that fit within a human's actual ground space. These can be used to avoid obstacles and enhance maneuverability [6-7]. With trajectory planning, the humanoid robot determines a suitable motion of the lower-limbs before actually performing motion by interpolating on-line human motion data during the swing and supporting Phases. If the lower-limb trajectories are designed to attain a specified goal, we can choose a set of constraints of its motion configuration properly.

B. *Adopting the bezier curve*

Generating Tasks for humanoid robot, it trace the path of a describing desired end effector, which were determined by motion configuration and convert these data into a kinematics transformation after dividing the motion into Phases. In the Task, it is necessary to interpolate from position to next position during the Phase to allow the humanoid robot to transit more skillfully. As interpolation algorithm, we were adopted a third-order bezier curve. This provides suitable smooth shape for end effector for the end effector of the humanoid robot by adjusting the control vectors and anchor parameters.

In general, the parameters for a third-order bezier curve can be expressed as $P = (P0, P1, \ldots, Pn\text{-}1, Pn)$. Here, $P1$ to $Pn\text{-}1$ are the control points, while $P0$ and Pn denote anchor points (one is initial position, $P_{initial}$ and the other is the desired end position, P_{end} in Phase). Therefore, trajectory generation by a third-order bezier curve consists of four points: two control and two position points. The control points are associated with shape of trajectories, which pull the curve vector in a given direction. Also, all of trajectory present with two points without description of via points. The interpolation equation using a third-order bezier curve is

$$X(t) = \sum_{i=0}^{n} B_{n,i}(t) P_i \qquad (\, i = 0, \ldots, n) \tag{1}$$

where,

$$B_{n,i}(t) = \frac{n!}{(n-i)!\,i!} t^i (1-t)^{n-i} \tag{2}$$

Eq.(2) describes the Bernstein polynomials, where t is an interval ranging from 0 to 1. The polynomials for a third-order bezier curve are obtained by substituting n = 3. Substituting Eq.(2) into Eq.(1), $X(t)$ becomes

$$X(t)=(1-t)^3P_0+3t\,(1-t)^2P_1+3t^2(1-t)\,P_2+t^3P_3 \tag{3}$$

Then, the Eq.(4) can be rewritten as a four-dimensional matrix form:

$$X(t) = [1 \;\; t \;\; t^2 \, t^3] \begin{bmatrix} 1 & 0 & 0 & 0 \\ -3 & 3 & 0 & 0 \\ 3 & -6 & 3 & 0 \\ -1 & 3 & -3 & 1 \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{bmatrix} \tag{4}$$

Here, the vector P_0, P_1, P_2 and P_3 denotes the control and anchor points of a third-order bezier curve.

IV. APPLICATION OF TASK

In order to generate Task widely, the data that gleaned from human motion strategy needs to re-use. It means previous data of motion by capturing system to generate new Tasks so that certain requirements should be met. Furthermore, an extended Task for application can be re-generated newly through the Phase Sequence and its composition method. This section describes stair climbing Task for humanoid robot using proposed method.

A. *Task Library*

We captured several subjects different motion sets for Task generation of humanoid robot using capturing system in real space. Although, humanoid robot would be demanded for many kinds of motion planning by programming according to capricious environments, it is hard to determine the Task that does exactly what humanoid robot wants because the acquired data from capturing experiments have limitation of quantity for Task.

To solve this problem, we adopt the Task library that can be constructed by individual preparing Phase. Extended Task, but not used capturing data, can be generated by Phase recomposition and reusing of library. Many number of Task in library as example would show in more variety and flexibility for humanoid robot. As library size grows, the ability to perform about an environment would become more and more selective. This library contains in individual Phase data that consists of transformed trajectories by kinematics constraints from configuration between desired position and orientation with interpolation, and recognition threshold for continuous Phase transition. Also, these Phases in Task library must be stored as named through threshold condition. Therefore, the size of constructed library would be keys to the success of an autonomous objective Task.

B. The Generation of Extended Task

To realize autonomous Task for humanoid robot in various environments, generating trajectories of each foot is important [6-7]. The desired lifting-off and step height position should be taught by actual human's fundamental motion, ascending and walking, and it operates for Task generation. Moreover, the trajectories are planned using third-order bezier curve because it can be defined by control points, which make it invariant shape. We need only to transform the control points and the compute the new trajectories.

1. The planning for stair climbing

In this section, we present the method of extended Task generation, such as stair climbing , through re-composition and re-using of previous constructed Phase that contain a generated trajectories based on modifying parameter of third-order bezier curve and transition, which are allowed during a contact change though position teaching. As seen in figure 7, stair climbing Task can be planned by classification of one-step ascending and walking, iterative leg transferring and COG, as follows.

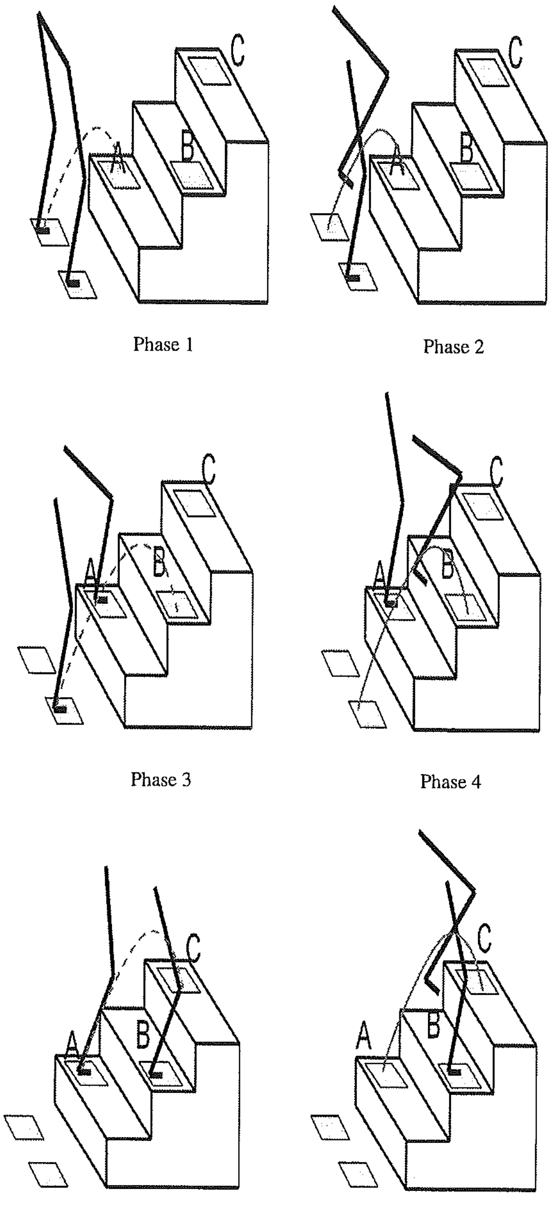
-Phase 1: The initial posture of COG moves on left leg in order to stable start. This Phase can be considered as same Phase 1 of ascending step, shown in figure 3.

-Phase 2: This period shows swing of leg to one-step. This leg allow predicting desired trajectory according to bezier curve parameter while planning trajectories to position A. One-step stride and height on stair can be determined in this procedure by referring re-using Phase 2 of ascending Task.

-Phase 3: This Phase expressed as a COG transferring on stair due to stable. Also, the trajectories of right leg would be planned by sequence via half of leg step to position A using Phase 3 in walking before shift to position B.

-Phase 4: In practice, the leg transition of stair climbing Task is done by planned trajectory in Phase 3. This leg is modified from leave the ground to another pose, which is about to arrive on the stair adopting parameter of bezier curve.

-Phase 5: The period, performing right COG, is similar to that of Phase 3. The position C can be considered as next step to arrive.



Phase 1 Phase 2

Phase 3 Phase 4

Phase 5 Phase 6

Fig.7 Trajectory planning for stair climbing by Phase division

-Phase 6: This position is final Phase of this Task. Also, left leg transition in this Phase can be referred via half of right leg step to position C re-using Phase 4 in walking. Also, the end of this Phase returns to the starting point for Phase 1.

In summary, stair climbing Task could be classified into six cyclic Phases, which composed by Phase of ascending and walking Task.

V. SIMULATION RESULTS

The result of simulation for regenerated stair climbing Task based on Phase re-composition and Phase Sequence algorithm. This simulation is tested in 10cm stair height and 25cm stride. Stair climbing Task is generated by referring Task library, which is contains a Phase that consists of motion parameter, position and orientation and threshold value for transition. Also, combining of previous Phase and Phase Sequence from ascending and walking Task was conducted. Its Phase is planned from the arrival and contact on ground position modifying third-order bezier curve. Then, humanoid robot could perform the stair climbing Task as shown in figure 8.

VI. CONCLUSION

This paper describes a method of extended Task generation for humanoid robot that is capable changing and environment conditions. Our approach is re-composition and re-using of Phase referring the previous data from captured human motion strategy, which is stored in library. The Task is generated by Phase Sequence method that defined as cyclical transition operation of individual Phase. We then modified parameter of third-order bezier curve to allow trajectory planning of Task into humanoid robot in capricious environments. Using this method, generation of extended Task would not require data of actual human motion from capturing system. A simulation result, stair climbing is classified into six Phases, which consists of previous two Tasks, ascending step and normal walking. Adopting Phase Sequence algorithm, this result was verified.

VII.REFERENCES

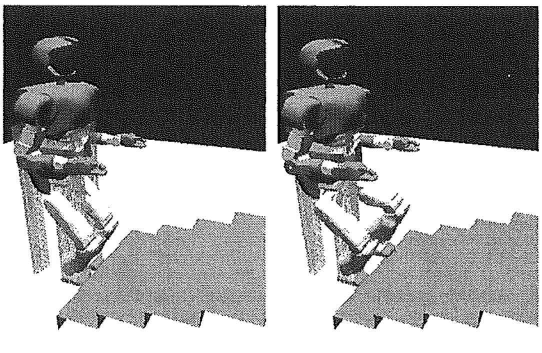
[1] G. Figliolini and M. Ceccarelli: "Climbing Stairs EP-WAR2 Biped Robot", *Proc. of International Conference on Robotics & Automation (ICRA2001)*

[2] Shinichiro Nakaoka, Atsushi Nakazawa, Kazuhito Yokoi, Hirohisa Hirukawa and Katsushi Ikeuchi: "Generating Whole Body Motions for a Biped Humanoid Robot from Captured Human Dances", *Proc of International Conference on Robotics & Automation (ICRA2003)*

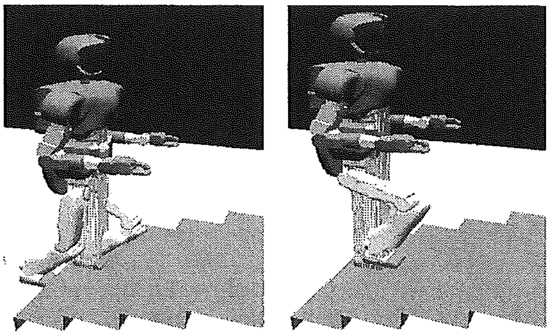
[3] Nancy S. Pollard, Jessica K. Hodgins, Marcia J. Riley, and Christopher G. Atkeson: "Adapting Human Motion for the Control of a Humanoid Robot" *Proc of International Conference on Robotics & Automation (ICRA2002)*

[4] Seong-Hoon KIM, Haruki IMAI, and Yoshiyuki SANKAI: "Interactive Task generation for Humanoid Based on Human Motion Strategy". *Proc of International Workshop on Robot and Human Interactive Communication(ROMAN2004)*

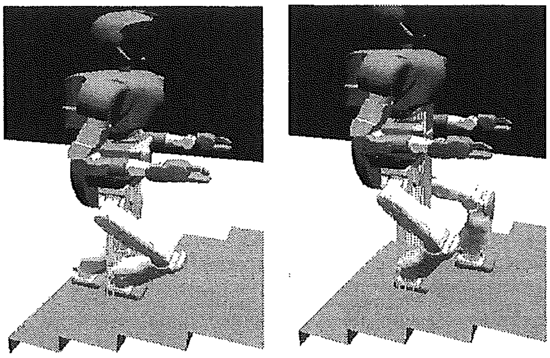
[5] Hiroaki Kawamoto, Shigehiro Kanbe, and Yoshiyuki Sankai: "Power Assist Method for HAL-3 Estimating Operator's Intention Based on Motion Information" *Proc. of International Workshop on Robot and Human Interactive Communication (ROMAN2003)*



Phase 1 Phase 2



Phase3 Phase 4



Phase 5 Phase 6

Fig.8 The result of extended Task, stair climbing, according to Phase composition and Phase Sequence method.

[6] Bizzi E, Accornero N, Chapple W, and Hogan N: "Posture control and trajectory formation during arm movement", *J .Nerosci 1984, 4: pp.2738-pp.2744*

[7] Qiang HUANG, Kenji KANEKO, Kazuhito YOKOI, Shunji KAJITA, Tetsuo KOTOKU, Noriho KOYACHI, Hirohiko ARAI, Nobuaki IMAMURA, Kiyoshi KOMORIYA, and Kazuo TANIE: "Balance Control a Biped Robot Combining Off-line Pattern with Real-time Modification", *Proc. of International Conference on Robotics & Automation, 2000 (ICRA2000). pp.3346-3352*

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Intention-Based Walking Support for Paraplegia Patient

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Abstract - *This paper proposes an algorithm to estimate human intentions during walking. Not only walk start or stop but walking cycle is considered as the intentions in this paper. The algorithm is embedded into a walking support system, a wearable robot "Robot Suit HAL-3", for paraplegia patients. The estimation of patients' intentions is indispensable for effective and comfortable motion support, but the biological signals such as myoelectricity which is used for the support by HAL-3 cannot be measured properly. The proposed algorithm, therefore, estimates patients' intentions from other channels such as a floor reaction force and a body posture. The effectiveness of this algorithm is investigated through experiments with two types of patients. One has a sensory paralysis on both legs, especially a left leg has severe trouble. The other has troubles in sensory and motor ability on both legs. We show HAL-3 supports patients' walk comfortably, estimating patient intentions.*

Keywords: Walking support, paraplegia, robot suit, HAL, intention, motion information, tracking control, gait pattern.

1 Introduction

Cerebral paralysis, stroke, infectious diseases such as polio, spinal cord injury and so on may cause various troubles on his/her motility, such as muscle rigidity or relaxation, involuntary contraction of muscle, and sensory paralysis. Most patients who have paraplegia on the lower limbs due to these symptoms are unable to walk and are bedridden all day long at worst. Moreover, there is a possibility to depress the patients' feelings, for instance bedridden patients lose his/her life worth living. Care givers including the patient's family receive hard works to look after him/her, once a person has a trouble in the motility. To relieve these problems and to support the patient's independent life, it is quite important to provide a safe and convenient transportation device.

As a transportation device for patients with gait disorder, a wheelchair now is used extensively. A wheelchair is convenient since it is inexpensive and enables to move easily as long as a little muscular power is left in upper limbs. Even if a patient has weakness of the arms and legs, a motorized wheelchair could be used. However, wheelchairs have other problems in its hardware and user matters. At first, the utility of a wheelchair depends on its environment. That is it is difficult to move on uneven footpath, and almost impossible to pass through small space such as a door sill and to climb up stairs. Second, it may cause physical damages on his/her body, such as weakness of the muscle, low bone density, autonomic dysfunction and pressure ulcer on his/her hip because the user keeps sitting posture for a long time. Third, wheelchair users may feel that they are looked down on by other people around because the height of eyes of the user tends to be lower than that of healthy people. Other type of transportation device that can solve these three problems mentioned above should be developed for a better welfare society. These problems could be solved if a patient with paraplegia can walk on his/her legs as a healthy person does. Therefore a device which makes a patient walk in his/her standing posture would be one of the solutions since he/she can locomote with his/her leg, receiving a physical support. In our study, we focus on the advantage of bipedal locomotion and develop a wearable type walking support system for a patient with paraplegia.

Up to now, several wearable robot systems for walking support have been developed. Pratt et al. have developed "RoboKnee" [1] to support the knee motion during walking or climbing up stairs. This system can support wearer's walk in exact timing with his/her motion and posture by estimating his/her intention through the knee joint angle and a floor reaction force. It is, however, difficult to support a patient with paraplegia since it is not able to support multiple joints in lower limbs simultaneously and to control his/her posture. Johnson et al. have developed a support system using pneumatic muscles by compressed gas not for a healthy person but for the paralyzed, amputee and spastic patient [2]. One of aims of this work was to solve problems about weight, power, endurance and cost of the actuators. Another significant feature is the handy operational interface to select system actions. All actions corresponding to the switches operations are controlled by wearer's hand. The operation is not, however, intuitive and a user has to get used to the complex operation. As with this system, TOYOTA has developed a robot named "i-foot" which motion a user could control by a joystick. The user gets on the robot with two legs and can move by the robot's bipedal locomotion according to the user's operation. It has a significant advantage to control easily, and it is easy to reflect the user's intentions. Physical problem to a patient discussed above, however, cannot be solved since this transportation compels the user to keep sitting posture. In our laboratory, "HAL (Hybrid Assistive Limb)" illustrated in Figure 1 has been developed for supporting wearer's daily activities and successfully supports healthy person's walk [3][4][5][6]. Mainly, HAL supports human activities based on wearer's biological signals including myoelectricity which reflects his/her intention. In addition, HAL mechanically can support patients with paraplegia as well as healthy persons since HAL can support functional motion with multiple joints simultaneously, covering whole of lower limbs.

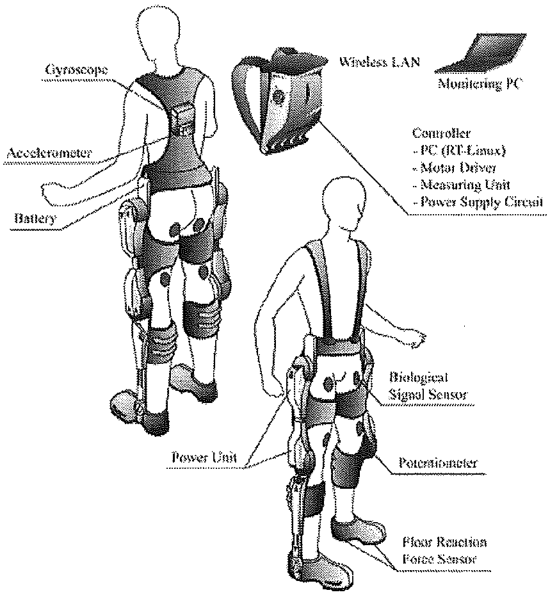


Figure 1. Configration of HAL system.

Based on those conventional works, two additional functions are embedded into HAL in order to develop the walking support system for a patient with paraplegia in this paper. First, a bipedal locomotion should be achieved by using his/her own legs. This function consists of swinging a leg, balancing the wearer's body and switching of a swing and support leg. Second, the robot should autonomously estimate wearer's intentions during walking in order to respond the wearer preference without time delay and any interface.

The purpose of this study is that HAL makes a patient with paraplegia walk in a standing posture. To implement above two functions, this paper introduces the following approaches.

1) To achieve the bipedal locomotion based on gait patterns of a healthy person.

We extract gait patterns from a healthy person's walk for the reference patterns to a patient. The healthy person's walking motion could be suitable to the patient if he/she has the same physical characteristics as the healthy person. However, the extracted motion should be adjusted according to a patient's physical constitution, and the algorithm to adjust the walking cycle is shown in section 4.1.

2) To synchronize support motions: the walk start, stop and the beginning to swing a leg, with wearer's intentions by measuring motion information.

The biological signals of patients such as myoelectricity are reliable information to estimate human intentions. In general, proper biological signal cannot be measured from a patient with paraplegia. We, therefore, propose an algorithm to estimate patients' intentions from motion information such as a floor reaction force and a body posture. The details are shown in section 4.2. The following sections explain assumptions of this study and introduce a robot suit "HAL-3" used in experiments before proposing the algorithm.

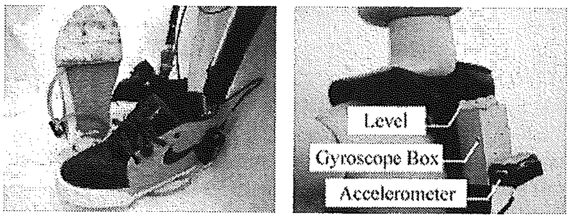
2 Assumptions and approach

In this paper, the proposed algorithm is applied to the walking support for two types of subjects. One has sensory paralysis on both legs, especially left leg because of spinal cord injury by traffic accident (Subject A). He can slowly walk by himself with two canes. The other, who is a healthy person, simulates a subject who cannot support even his weight by himself (Subject B). This case is to verify the possibility to apply the algorithm to a patient with entirely muscular relaxation in lower limbs. He tries to relax his lower limbs in order to simulate such a patient. In these cases, we cannot measure proper biological signals to estimate a subject's intention because of disorder of neuraltransmission. We, therefore, use proper motion information for patient's symptoms instead of biological signals in this experiment. Floor reaction force (FRF) is measured for subject A. Angle of wearer's torso on lateral plane is measured for subject B. It should be noted that our algorithm synchronizes walking motion with his/her intention by using not any external operational devices such as a joystick but motion information during walking. The intention generally contains stride length and walking direction in addition to walk start, stop and walking cycle that are dealt with in this paper.

The stability control of wearer's posture is desired for a practical transportation device used in daily life. In this paper, however, the patients are supposed to keep their own stability by holding on a walking flame with their upper body and arms.

3 Robot suit HAL

In the experiment, the robot suit HAL-3 is used. HAL-3 consists of a power unit, exoskeletal flames, sensors and a controller. DC servo motors as the power unit are attached on each hip and knee joints and actuate each joint through the harmonic drive gear. The exoskeletal flames are fixed to wearer's legs with molded plastics, and transmit torque of the motor to his/her legs. There are various sensors including angular sensors, FRF sensors and gyroscope to measure motion information of HAL-3 and a wearer and to estimate wearer's intentions. Potentiometers as angular sensors are attached to the each joint to measure the joint angle. FRF sensors utilizing the semiconductor-type pressure sensor are implemented in the front and rear of shoe sole. Figure 2(a) shows the appearance of FRF sensors. Three rate gyroscopes located in the gyroscope box (Figure 2(b)) measure three angles of wearer's torso by integrating the measured angular velocity data. In this paper, a rotation angle in roll axis among three rotational axes is focused to acquire the angle of wearer's torso on wearer's lateral plane. In addition, a computer, motor drivers and a power-supply unit is aggregated in a backpack as the controller of HAL-3. The controller can gather the measured data from those sensors and control DC servo in real-time.



(a) (b)

Figure 2. Sensors for intention estimation.

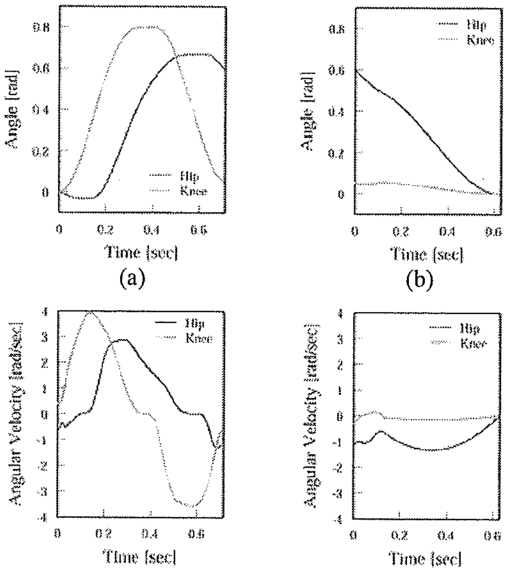
(a) is floor reaction force sensors, and (b) is measurement system for wearer's body posture.

4 Controller design for walk support

In this section, we explain a controller for walking support system. The reference pattern extracted from healthy person's walk is used for proportional and derivative (PD) control for the corresponding joints of a wearer. The reference pattern is divided into two sub-patters that are swing leg pattern and support leg pattern. Each pattern is used for the corresponding leg's control synchronizing with wearer's intention estimated by our proposed algorithm. In the following sub-section, the details of the controller are shown.

4.1 Reference pattern extraction

As mentioned above, the walking support is achieved by applying reference gait patterns measured in healthy person's walk. The gait patterns of a swing leg and a support leg are extracted independently each other. The time scales of the reference patterns are linearly shorten or lengthen so that the walking cycle could be adjusted to a wearer's intention or a wearer's physical constitution. For example Figure 3 shows the reference patterns extracted from a healthy person's walk.



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

Figure 3. Reference gait patterns.

(a) and (b) show angle patterns of a swing leg and support leg, respectively. (c) and (d) show angular velocity patterns of a swing leg and support leg, respectively.

4.2 Intention estimation

The intention estimation is indispensable to synchronize motion supports with the wearer's intentions. The floor reaction force is used for an intention estimation of the subject A and the torso angle is for that of the subject B. The floor reaction force reflects the position of center of gravity (COG) and COG could be the reliable information for the intention estimation. For example a leg could leave a floor and work as a swing leg safely if it does not support his/her weight. On the other hand, other information should be used if a reliable FRF could not be measured due to muscular weakness such as the subject B's symptom. The legs of the subject B do not support his weight because his muscle does not receive proper stimulation from his nerve system due to spinal cord injury. A torso angle could be the second reliable information for wearer's intention, because the COG and torso angle has close relationship.

4.2.1 FRF-based estimation

A support system "HAL" estimates which leg supports a wearer's weight. For example, a right leg becomes a support leg and a left leg becomes a swing leg when an inequality (1) is satisfied;

$$f_r > f_l \qquad (1)$$

where the f_r and f_l are FRF of right and left foot, respectively. On the other hand, a left leg becomes a support leg when an inequality (2) is satisfied;

$$f_r < f_l. \tag{2}$$

HAL can allocate the roles of two legs: swing or support leg and start walking support with this algorithm if the subject supports his/her weight almost by himself.

4.2.2 Torso-angle-based estimation

In healthy person's walk, it is said that he/she tilts his/her torso up to about 0.07 [rad] from a perpendicular line. The torso angle is almost synchronized with the FRF transition. A torso angle, therefore, becomes key information even if the FRF is not measured due to entirely muscle relaxation. In this study, we focus on the angle of the torso on the wearer's lateral plane during walking in order to estimate a wearer's intention. We set an upper threshold (θ_+ = 0.05 [rad]) and a lower threshold (θ_- = -0.05 [rad]) shown in Figure 4. HAL estimates that the wearer intends to exchange a role of right leg from support leg to swing leg and vice versa when an inequality (3) is satisfied as follows;

$$\theta_p > \theta_+ \tag{3}$$

where his angle of the torso is θ_p. When an inequality (4) is satisfied, HAL estimates that the wearer intends to exchange a role of right leg from swing leg to a support leg and vice versa.

$$\theta_p < \theta_-. \tag{4}$$

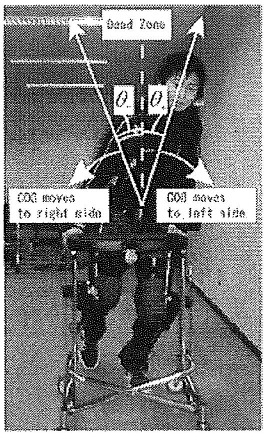


Figure 4. Torso angle during walking.

4.3 Control architecture

Bipedal locomotion using patient's legs is achieved by the tracking control and by phase synchronization of motion support with patient's intention. This control is the PD control using reference gait patterns based on healthy person's walk as shown in Figure 3. Figure 5 shows the block diagram for this tracking control and phase synchronization. The human intention estimator (HIE) located in the upper-left part in the figure has the FRF or the torso angle as input for the estimation algorithms described in the section 4.2. Two blocks under HIE are a library of the reference patterns for swing and support legs. HIE allocates these reference patterns to two legs during walking. There are four ordinary PD control blocks on the right side of HIE and the library. The upper two blocks are controllers for the right leg and the lower ones are for the left leg. The command voltages $\boldsymbol{\tau}$ to the power units are calculated by

$$\boldsymbol{\tau}_r = \mathbf{k}_r(\mathbf{q}_{ref\_r} - \mathbf{q}_r) + \mathbf{k}'_r(\dot{\mathbf{q}}_{ref\_r} - \dot{\mathbf{q}}_r) \tag{5}$$

$$\boldsymbol{\tau}_l = \mathbf{k}_l(\mathbf{q}_{ref\_l} - \mathbf{q}_l) + \mathbf{k}'_l(\dot{\mathbf{q}}_{ref\_l} - \dot{\mathbf{q}}_l) \tag{6}$$

where $\mathbf{q}_r$ and $\mathbf{q}_l$ are the actual wearer's leg joint angles, subscripts r and l mean right and left, respectively, $\dot{\mathbf{q}}_r$ and $\dot{\mathbf{q}}_l$ are angular velocities, $\mathbf{q}_{ref\_r}$, $\mathbf{q}_{ref\_l}$, $\dot{\mathbf{q}}_{ref\_r}$ and $\dot{\mathbf{q}}_{ref\_l}$ are the reference joints angles and the reference angular velocities, respectively. These variables have four elements that correspond to four joints: right and left hip joints and knee joints. In addition, feedback gains $\mathbf{k}_r$, $\mathbf{k}_l$, $\mathbf{k}'_r$ and $\mathbf{k}'_l$ are diagonal matrixes where feedback gains for each joint are diagonal elements. The different feedback gains are used in the swinging or supporting phase independently, by adopting this control architecture. Figure 6 shows the control flow for the walking support. When the HAL starts the PD control for all joints once the condition shown eq. (1) or (2) is satisfied in a case of the first algorithm for intention estimation. The PD control continues until HAL finishes the reference pattern. If the other condition is not satisfied after this control, the next control is not started and two legs are kept at the final posture of the step. In a case of the second algorithm for intention estimation, the same control flow is implemented, just exchanging the condition of eq. (1) and (2) with the condition of eq. (3) and (4). This algorithm can synchronize walking support with human intention at a walk start instance, a walk stop instance as well as the beginning of leg swing during walk. In addition to those walking support, HAL compensates viscosity and static friction of the power unit and weight of HAL itself.

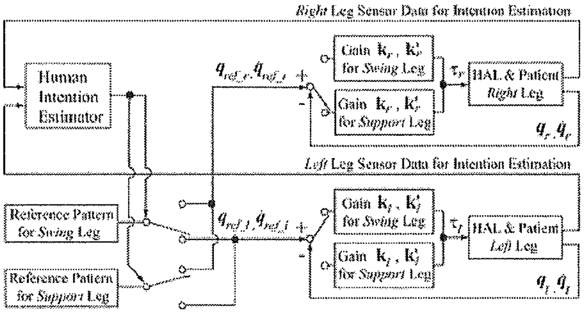


Figure 5. Block diagram for tracking control.

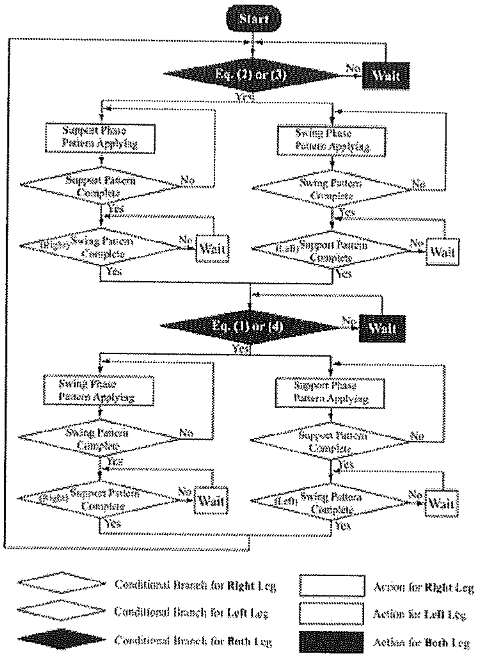


Figure 6. Flowchart for walking support.

5 Experiment

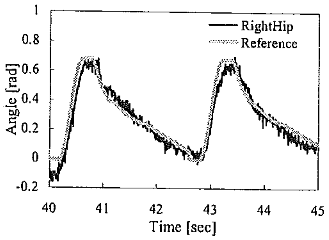
5.1 Support for subject A

Subject A is the patient who has a strong sensory paralysis especially on the left leg and who can walk slowly using two canes with his both hands. Since he can stand by himself, the support aim with HAL is to help his leg swinging forward and sustaining his weight. This leads to stabilize his walk by pushing a swing leg forward and by avoiding collisions of a swing leg with a floor.

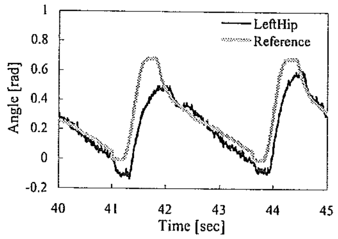
Figure 7 (a), (b), (c) and (d) show his each joint angle and the references during walking support. From the results in (a) and (b), his hip joints followed the reference patterns. On the other hand, the results in (c) and (d) show his knee joints did not follow the reference patterns very well, especially knee joint on his left leg which has a severe sensory trouble. The low feedback gains for his knee joints results in this poor tracking because the higher gain causes a subject discomfort feeling in the early stage. That is the reason why the subject has own walking pattern without any support and he is not used to receive other people's waking pattern. As another reason of the discomfort, the swing leg might be let passively swing without any support since a swing leg of a healthy person is almost passive. Table 1 shows the stride length of each leg in a walk without and with HAL's support. Equation (7) calculates the stride length based on the link model shown in Figure 8.

$$L = \{l_{r\_upper}\sin\theta_r + l_{r\_lower}\sin(\theta_r - \varphi_r)\} - \{l_{l\_upper}\sin\theta_l + l_{l\_lower}\sin(\theta_l - \varphi_l)\} \qquad (7)$$

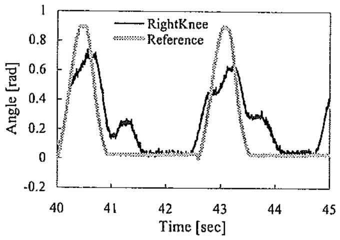
where θ_r and θ_l are his right and left hip joint angles, φ_r and φ_l are knee joint angles, l_{r_upper} and l_{l_upper} are thigh length, and l_{r_lower} and l_{l_lower} are lower leg length. Torsional motion of a pelvis part during walking is not considered for simplification.



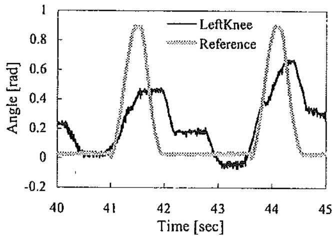
(a) Angle of right hip joint.



(b) Angle of left hip joint.



(c) Angle of right knee joint.



(d) Angle of left knee joint.

Figure 7. Joint angle and reference pattern for subject A.

Table 1. Stride length.

	Left leg	Right leg
Normal walk	0.40[m]	0.44[m]
Supported walk	0.41[m]	0.48[m]
Rate of enlargement	2.5[%]	9.1[%]

Table 1 shows that the stride length is enlarged by HAL's support on both legs. Especially, the rate of enlargement on the right leg is 9.1 [%]. Generally a walking stability becomes lower when the stride length is enlarged since the motion becomes bigger and faster. HAL would achieve the higher stability so that the subject can enlarge his stride length keeping his walking stability.

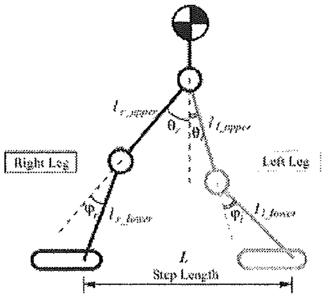


Figure 8. Lower limb model for stride length calculation.

5.2 Support for subject B

Subject B can neither walk nor keep standing position without supporting aids due to fully muscular relaxation. In this study he is simulated by a healthy person. The subject sways his torso from side to side in order to express his walk intention, by using his arms that hold a walk flame as shown in Figure 9. Functions realized by HAL are to keep standing position and to swing his legs forward based on his intention. In this case, the feedback gain is larger than the previous experiment due to full replacement of his muscle.

Figure 10 shows torso angle and phase transition during one walking cycle supported by HAL. The upper figure shows the angle and the raw angular velocity from the gyroscope, and the lower one shows the function phase transition during a walking cycle. The right leg performs the support leg up to 22.1 [sec] and then keeps the current angles until HAL detects his intention of the next step. His torso swings from right to left, and the equation (3) is satisfied at 22.5 [sec] as shown in the upper figure. HAL then begins to swing the right leg. HAL supports the subject B walk synchronizing his intentions. Figure 11 (a), (b), (c) and (d) show his each joint angle and the references during walking support. From the results in (a) and (b), his hip joints followed the reference patterns. On the other hand, the results in (c) and (d) show that his knee joints do not periodically follow the references in a part of the walking cycle since the foot of a swing leg lands earlier than a healthy person. The early landing is caused by a mechanical difference between a healthy person and a subject with HAL. The healthy person uses ankle joint to kick a floor with a toe as shown in Figure 12(a), but the subject does not use his ankle due to no support from HAL at the ankle joint as shown in Figure 12(b). A foot height of a swing leg of the subject is, therefore, lower than that of a healthy person.

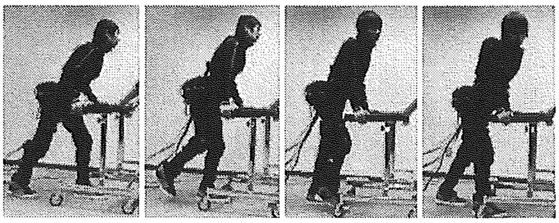


Figure 9. One step in walking support for subject B.

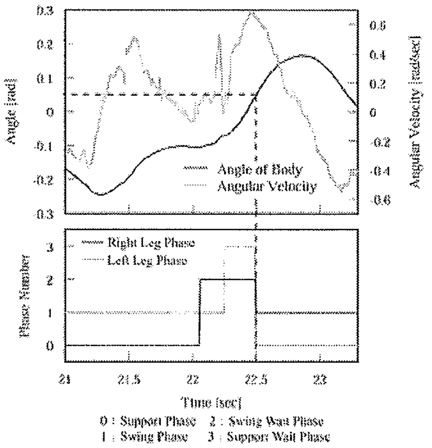
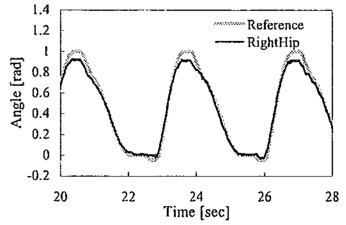
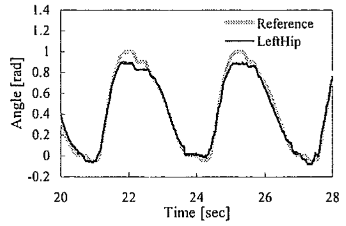


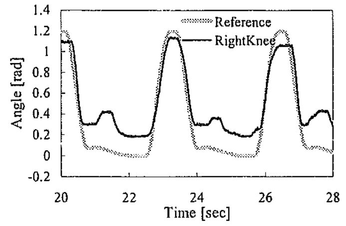
Figure 10. Angle of wearer's torso and phase transition.



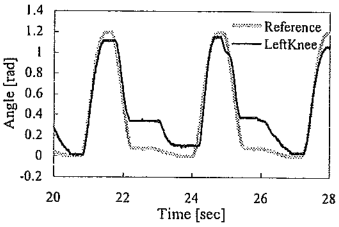
(a) Angle of right hip joint.



(b) Angle of left hip joint.



(c) Angle of right knee joint.



(d) Angle of left knee joint.

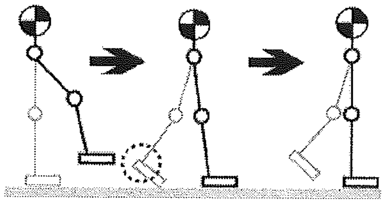
Figure 11. Joint angle and reference pattern for subject B.

The earlier landing could be compensated if the actuator on the knee joint had enough torque. Figure 13 shows a vertical load affecting one support leg due to gravity. The necessary torque of the knee joint is calculated by the following equation;

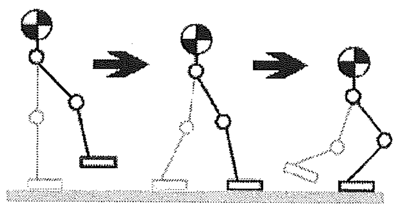
$$\tau_{knee} = mgl \tag{8}$$

$$l = l_l \sin\theta \tag{9}$$

where m is his weight, g is gravity acceleration, l is the distance of the knee joint to the COG line, l_l is the length of the lower leg and θ is the knee angle from the vertical line depicted in Figure 13(b). In the case of the standing posture without any bending joints shown in (a), there is no joint torque needed theoretically. On the other hand, if the knee joint is bended even a little, HAL support knee joint for keeping standing posture. The larger the joint bends, the more torque is needed. Figure 11 (c) and (d) shows HAL cannot support his weight by one power unit on his knee joint since the knee joint at landing instance is beyond the torque tolerance.

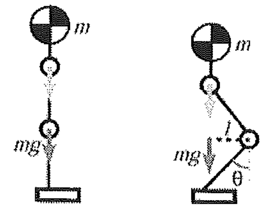


(a) Healthy person's walk.



(b) Subject B's walk supported by HAL.

Figure 12. Joint motion of support leg.



(a) (b)

Figure 13. Joint torque to support weight.

6 Conclusions

In this paper, we have proposed the algorithm to estimate patients' intentions so that the HAL-3 could support a patient with paraplegia to walk. Two algorithms are proposed for the different types of patients. One is FRF-based estimation and the other is torso-angle-based estimation. The cycle of reference walking pattern is adjusted for each patient and the walk support based on the reference gait is achieved, synchronizing with patients' intentions estimated by the algorithm. We confirmed that two algorithm could estimate corresponding patients' intentions.

Acknowledgment

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References

[1] Jerry E. Pratt, Benjamin T. Krupp, Christopher J. Morse and Steven H. Collins: "The RoboKnee: An Exoskeleton for Enhancing Strength and Endurance During Walking", Proceedings of the 2004 IEEE International Conference on Robotics and Automation (ICRA '04), pp.2430-2435, 2004.

[2] David C. Johnson, Daniel W. Repperger and Greg Thompson: "Development of a mobility assist for the paralyzed, amputee, and spastic patient", Proceedings of the IEEE Southern Biomedical Engineering Conference, pp.67-70, 1996.

[3] Y. Sankai, H. Tanaka, J. Okamura: "EMG Based Prototype Powered Assistive System for Walking Aid", Proc. of ASIAR, pp.229-234, 1999.

[4] Hiroaki Kawamoto and Yoshiyuki Sankai: "Comfortable Power Assist Control Method for Walking Aid by HAL-3", Proc. of International Conference on Systems, Man and Cybernetics (SMC2002), 2002.

[5] Hiroaki Kawamoto and Yoshiyuki Sankai: "Power Assist System HAL-3 for Gait Disorder Person", Proc. of ICCHP 2002 International Conference on Computers Helping People with Special Needs, pp.196-203, 2002.

[6] Hiroaki Kawamoto, Shigehiro Kanbe, and Yoshiyuki Sankai: "The Natural Frequency-Based Power Assist Control for Lower Body with HAL-3", Proc. of 12th IEEE Workshop on Robot and Human Interactive Communication (ROMAN2003), 2003.

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Intention-Based Walking Support for Paraplegia Patient

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Abstract - *This paper proposes an algorithm to estimate human intentions during walking. Not only walk start or stop but walking cycle is considered as the intentions in this paper. The algorithm is embedded into a walking support system, a wearable robot "Robot Suit HAL-3", for paraplegia patients. The estimation of patients' intentions is indispensable for effective and comfortable motion support, but the biological signals such as myoelectricity which is used for the support by HAL-3 cannot be measured properly. The proposed algorithm, therefore, estimates patients' intentions from other channels such as a floor reaction force and a body posture. The effectiveness of this algorithm is investigated through experiments with two types of patients. One has a sensory paralysis on both legs, especially a left leg has severe trouble. The other has troubles in sensory and motor ability on both legs. We show HAL-3 supports patients' walk comfortably, estimating patient intentions.*

Keywords: Walking support, paraplegia, robot suit, HAL, intention, motion information, tracking control, gait pattern.

1 Introduction

Cerebral paralysis, stroke, infectious diseases such as polio, spinal cord injury and so on may cause various troubles on his/her motility, such as muscle rigidity or relaxation, involuntary contraction of muscle, and sensory paralysis. Most patients who have paraplegia on the lower limbs due to these symptoms are unable to walk and are bedridden all day long at worst. Moreover, there is a possibility to depress the patients' feelings, for instance bedridden patients lose his/her life worth living. Care givers including the patient's family receive hard works to look after him/her, once a person has a trouble in the motility. To relieve these problems and to support the patient's independent life, it is quite important to provide a safe and convenient transportation device.

As a transportation device for patients with gait disorder, a wheelchair now is used extensively. A wheelchair is convenient since it is inexpensive and enables to move easily as long as a little muscular power is left in upper limbs. Even if a patient has weakness of the arms and legs, a motorized wheelchair could be used. However, wheelchairs have other problems in its hardware and user matters. At first, the utility of a wheelchair depends on its environment. That is it is difficult to move on uneven footpath, and almost impossible to pass through small space such as a door sill and to climb up stairs. Second, it may cause physical damages on his/her body, such as weakness of the muscle, low bone density, autonomic dysfunction and pressure ulcer on his/her hip because the user keeps sitting posture for a long time. Third, wheelchair users may feel that they are looked down on by other people around because the height of eyes of the user tends to be lower than that of healthy people. Other type of transportation device that can solve these three problems mentioned above should be developed for a better welfare society. These problems could be solved if a patient with paraplegia can walk on his/her legs as a healthy person does. Therefore a device which makes a patient walk in his/her standing posture would be one of the solutions since he/she can locomote with his/her leg, receiving a physical support. In our study, we focus on the advantage of bipedal locomotion and develop a wearable type walking support system for a patient with paraplegia.

Up to now, several wearable robot systems for walking support have been developed. Pratt et al. have developed "RoboKnee" [1] to support the knee motion during walking or climbing up stairs. This system can support wearer's walk in exact timing with his/her motion and posture by estimating his/her intention through the knee joint angle and a floor reaction force. It is, however, difficult to support a patient with paraplegia since it is not able to support multiple joints in lower limbs simultaneously and to control his/her posture. Johnson et al. have developed a support system using pneumatic muscles by compressed gas not for a healthy person but for the paralyzed, amputee and spastic patient [2]. One of aims of this work was to solve problems about weight, power, endurance and cost of the actuators. Another significant feature is the handy operational interface to select system actions. All actions corresponding to the switches operations are controlled by wearer's hand. The operation is not, however, intuitive and a user has to get used to the complex operation. As with this system, TOYOTA has developed a robot named "i-foot" which motion a user could control by a joystick. The user gets on the robot with two legs and can move by the robot's bipedal locomotion according to the user's operation. It has a significant advantage to control easily, and it is easy to reflect the user's intentions. Physical problem to a patient discussed above, however, cannot be solved since this transportation compels the user to keep sitting posture. In our laboratory, "HAL (Hybrid Assistive Limb)" illustrated in Figure 1 has been developed for supporting wearer's daily activities and successfully supports healthy person's walk [3][4][5][6]. Mainly, HAL supports human activities based on wearer's biological signals including myoelectricity which reflects his/her intention. In addition, HAL mechanically can support patients with paraplegia as well as healthy persons since HAL can support functional motion with multiple joints simultaneously, covering whole of lower limbs.

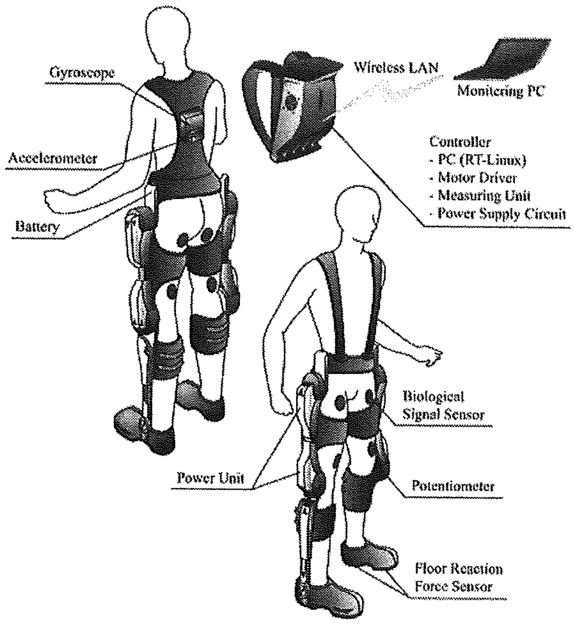


Figure 1. Configration of HAL system.

Based on those conventional works, two additional functions are embedded into HAL in order to develop the walking support system for a patient with paraplegia in this paper. First, a bipedal locomotion should be achieved by using his/her own legs. This function consists of swinging a leg, balancing the wearer's body and switching of a swing and support leg. Second, the robot should autonomously estimate wearer's intentions during walking in order to respond the wearer preference without time delay and any interface.

The purpose of this study is that HAL makes a patient with paraplegia walk in a standing posture. To implement above two functions, this paper introduces the following approaches.

1) To achieve the bipedal locomotion based on gait patterns of a healthy person.

We extract gait patterns from a healthy person's walk for the reference patterns to a patient. The healthy person's walking motion could be suitable to the patient if he/she has the same physical characteristics as the healthy person. However, the extracted motion should be adjusted according to a patient's physical constitution, and the algorithm to adjust the walking cycle is shown in section 4.1.

2) To synchronize support motions: the walk start, stop and the beginning to swing a leg, with wearer's intentions by measuring motion information.

The biological signals of patients such as myoelectricity are reliable information to estimate human intentions. In general, proper biological signal cannot be measured from a patient with paraplegia. We, therefore, propose an algorithm to estimate patients' intentions from motion information such as a floor reaction force and a body posture. The details are shown in section 4.2. The following sections explain assumptions of this study and introduce a robot suit "HAL-3" used in experiments before proposing the algorithm.

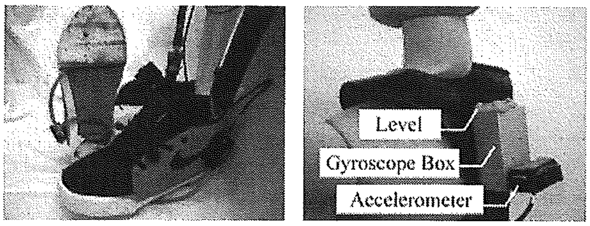
2 Assumptions and approach

In this paper, the proposed algorithm is applied to the walking support for two types of subjects. One has sensory paralysis on both legs, especially left leg because of spinal cord injury by traffic accident (Subject A). He can slowly walk by himself with two canes. The other, who is a healthy person, simulates a subject who cannot support even his weight by himself (Subject B). This case is to verify the possibility to apply the algorithm to a patient with entirely muscular relaxation in lower limbs. He tries to relax his lower limbs in order to simulate such a patient. In these cases, we cannot measure proper biological signals to estimate a subject's intention because of disorder of neuraltransmission. We, therefore, use proper motion information for patient's symptoms instead of biological signals in this experiment. Floor reaction force (FRF) is measured for subject A. Angle of wearer's torso on lateral plane is measured for subject B. It should be noted that our algorithm synchronizes walking motion with his/her intention by using not any external operational devices such as a joystick but motion information during walking. The intention generally contains stride length and walking direction in addition to walk start, stop and walking cycle that are dealt with in this paper.

The stability control of wearer's posture is desired for a practical transportation device used in daily life. In this paper, however, the patients are supposed to keep their own stability by holding on a walking flame with their upper body and arms.

3 Robot suit HAL

In the experiment, the robot suit HAL-3 is used. HAL-3 consists of a power unit, exoskeletal flames, sensors and a controller. DC servo motors as the power unit are attached on each hip and knee joints and actuate each joint through the harmonic drive gear. The exoskeletal flames are fixed to wearer's legs with molded plastics, and transmit torque of the motor to his/her legs. There are various sensors including angular sensors, FRF sensors and gyroscope to measure motion information of HAL-3 and a wearer and to estimate wearer's intentions. Potentiometers as angular sensors are attached to the each joint to measure the joint angle. FRF sensors utilizing the semiconductor-type pressure sensor are implemented in the front and rear of shoe sole. Figure 2(a) shows the appearance of FRF sensors. Three rate gyroscopes located in the gyroscope box (Figure 2(b)) measure three angles of wearer's torso by integrating the measured angular velocity data. In this paper, a rotation angle in roll axis among three rotational axes is focused to acquire the angle of wearer's torso on wearer's lateral plane. In addition, a computer, motor drivers and a power-supply unit is aggregated in a backpack as the controller of HAL-3. The controller can gather the measured data from those sensors and control DC servo in real-time.



(a) (b)

Figure 2. Sensors for intention estimation.

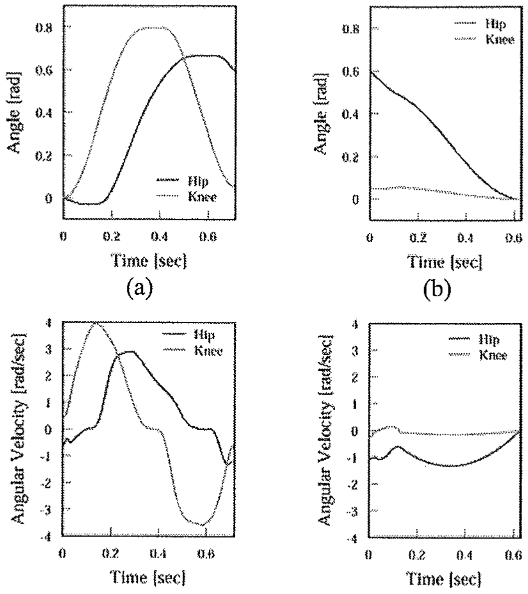
(a) is floor reaction force sensors, and (b) is measurement system for wearer's body posture.

4 Controller design for walk support

In this section, we explain a controller for walking support system. The reference pattern extracted from healthy person's walk is used for proportional and derivative (PD) control for the corresponding joints of a wearer. The reference pattern is divided into two sub-patters that are swing leg pattern and support leg pattern. Each pattern is used for the corresponding leg's control synchronizing with wearer's intention estimated by our proposed algorithm. In the following sub-section, the details of the controller are shown.

4.1 Reference pattern extraction

As mentioned above, the walking support is achieved by applying reference gait patterns measured in healthy person's walk. The gait patterns of a swing leg and a support leg are extracted independently each other. The time scales of the reference patterns are linearly shorten or lengthen so that the walking cycle could be adjusted to a wearer's intention or a wearer's physical constitution. For example Figure 3 shows the reference patterns extracted from a healthy person's walk.



(a) (b)

(c) (d)

Figure 3. Reference gait patterns.

(a) and (b) show angle patterns of a swing leg and support leg, respectively. (c) and (d) show angular velocity patterns of a swing leg and support leg, respectively.

4.2 Intention estimation

The intention estimation is indispensable to synchronize motion supports with the wearer's intentions. The floor reaction force is used for an intention estimation of the subject A and the torso angle is for that of the subject B. The floor reaction force reflects the position of center of gravity (COG) and COG could be the reliable information for the intention estimation. For example a leg could leave a floor and work as a swing leg safely if it does not support his/her weight. On the other hand, other information should be used if a reliable FRF could not be measured due to muscular weakness such as the subject B's symptom. The legs of the subject B do not support his weight because his muscle does not receive proper stimulation from his nerve system due to spinal cord injury. A torso angle could be the second reliable information for wearer's intention, because the COG and torso angle has close relationship.

4.2.1 FRF-based estimation

A support system "HAL" estimates which leg supports a wearer's weight. For example, a right leg becomes a support leg and a left leg becomes a swing leg when an inequality (1) is satisfied;

$$f_r > f_l \tag{1}$$

where the f_r and f_l are FRF of right and left foot, respectively. On the other hand, a left leg becomes a support leg when an inequality (2) is satisfied;