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Cooperative walk control of paraplegia patient and assistive system

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Abstract— **This paper introduces a cooperative control algorithm that designs a stable biped walk satisfying a wearer's intention relating to his/her walk such as a timings to start and stop walking, walking speed and waking direction. Using this algorithm an exoskeletal walking support system could help a paraplegia patient walking comfortablly. At first, a pair of gloves with several DOFs is developed to convey a wearer's intention to the walking support system. He/she swings both his/her index fingers as to simulate foot motions of his/her walking. The amplitude and period of the swing corresponds to a step length and period of the walk, respectively. Pronation/supination of the wrist joint of his/her right arm corresponds to a walk direction. The cooperative control algorithm based on a cart-table model designs trajectories of each joint for stable walking pattern that satisfies the intention expressed by the wearer's hand motion and then the designed walking pattern is executed in realtime by the walking support system. As the first trial, a small humanoid robot "HRP-2m" is used for safety as a control target that will be a combination of a wearer and the walking support system in the final situation. Through some experiments we confirm that our proposed algorithm enables the humanoid robot to start and stop stable walk with variable step length in the desired walking direction according to operator's intentions.**

I. INTRODUCTION

A wheelchair is now used in daily cases as a transportation device for patients with gait disorder. It is easy for the patients to start using a wheelchair because its mechanism is simple and it becomes available if enough muscular power remains in their upper body. Even if a patient has weakness of the arms, a motorized wheelchair could be used. However, wheelchairs have some problems relating to the user's environment and the user's posture. In particular, wheelchair users are apt to keep a sitting posture for a long time and have less opportunity to exercise their own lower bodies. That may cause a decrease in not only muscular power of the lower body with paralysis, but also residual physical functions such as bone density, vascular system and so on. These problems could be solved if a patient with paraplegia could walk on his/her own legs as a healthy person does. Therefore, a device which helps a patient walk in their standing posture would be one of the solutions since the patient can locomote with their legs receiving physical support.

Several devices for walking support have been developed[1]-[10]. In our study, a wearable-type robot "Robot Suit HAL" (Hybrid Assistive Limb) [12] has been developed in order to physically support a wearer's daily activities and heavy work. To provide effective physical support according to each wearer's condition, the control algorithm including an interface is very important as well as mechanisms of supporting devices. The HAL mainly uses a "cybernic voluntary control" to support a healthy person's motion. The cybernic voluntary control provides physical support according to the patients's voluntary muscle activity. The power units of the HAL amplify the wearer's own joint torque that is estimated from his/her bioelectrical signals. Bioelectrical signals including myoelectricity are useful and reliable information to estimate a healthy human's motion intentions because the signals are measured just before corresponding visible muscle activities. The HAL can physically support patients with some handicaps on their lower limbs as well as healthy people because HAL supports functional motions with multiple joints simultaneously, covering the whole of the lower limbs.

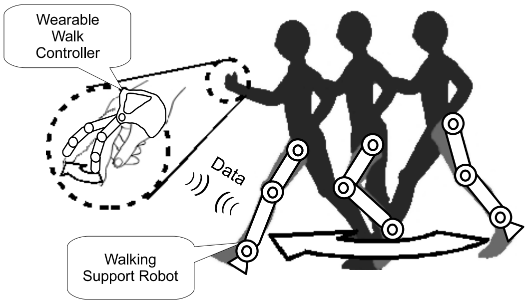

Fig. 1. Walking support system with wearable controller

However, as a whole, the cybernic voluntary control is not valid to a patient with a gait disorder because the signals that induce a broken walking pattern are not used for the power assist. 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, a cybernic autonomous control could provide effective physical support. The cybernic autonomous controller provides a desired functional motion designed 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 in cybernic autonomous control. HAL-5 Type-C with an estimation algorithm of a patient's intentions supported a complete spinal cord injury patient with sensory and motor paralysis on both legs to stand-up and to walk[12],tsukahara. The algorithm successfully estimated

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a patient's intentions associated with the start and stop of walking and stand-up. However not all kinds of a patient's intentions relating to the foot motions could be estimated since the information observed from the foot reaction force of the foot is limited.

This paper proposes another approach to convey various intentions relating with a foot motion precisely and intuitively so that the exoskeleton could support a paraplegia patient with a complete spinal cord injury to walk satisfying various preference of the patient. This is an intermediate approach of the voluntary control and the autonomous control because an upper limb of a paraplegia patient is used to control his/her lower limb with the exoskeleton support system. The patient swings both his/her index fingers as to simulate foot motions of his/her walking. The exoskeleton support system physically assist the patient legs so that they could mimic the finger motion. The amplitude and period of the finger swing corresponds to a step length and period of the walk, respectively. Pronation/supination angular velocity of the wrist joint of his/her right arm corresponds to a walk direction. Some DOFs of the lower limb are therefore used to realize a walk at the desired walking speed in the desired walk direction given by the patient through a wearable controller. The other DOFs are used for the exoskeleton to stabilize the patient posture during his/her walk.

To realize a cooperative biped control with a human and the exoskeleton, a wearable walk controller is developed to read wearer's intention from motions of a wearer's index fingers and wrist. Besides the cooperative control algorithm is proposed in this paper, that designs trajectories of each joint of the exoskeleton for stable walking pattern satisfying the wearer's intention. As the first trial, a small humanoid robot "HRP-2m" is used for safety as a control target that is a substitution of a combination of a wearer and the walking support system in the practical situation. Through some experiments we confirm that our proposed algorithm enables the humanoid robot to start and stop stable walk with variable step length and period in the desired walking direction according to operator's intentions.

II. WALKING SUPPORT SYSTEM WITH WEARABLE CONTROLLER

A. System architecture

The final goal of our study is that a paraplegia patient with a complete spinal cord injury walks as if he/she was a healthy person. As far the paraplegia patient, commands from his/her brain are not transmitted from the injured spinal cord to the more distant parts of the body. No signal is therefore observed on the paralyzed muscles in the severest case. In our study, the patient's intention or preference is observed from operations of his/her upper limb. Not all of six DOFs of the patient's lower limb is controlled by his/her upper limb. The patient just expresses his/her intention relating with a walk such as a stride length, period and a walk direction by using his/her upper limb. The system designs trajectories of each joint of the assistive system for stable walking pattern that satisfies his/her intention and then the designed walking pattern is executed in realtime by the assistive system. Some DOFs of the lower limb are therefore used to realize a walk at the desired walk. The other DOFs are used to stabilize the patient posture during his/her walk.

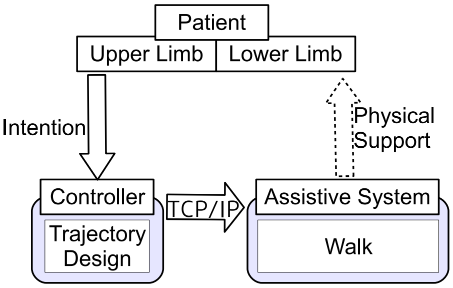


Fig. 2. System architecture

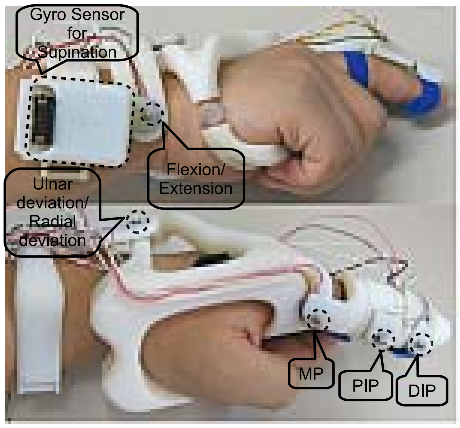


Fig. 3. Wearable walk controller. Upper figure shows a controller attached on right hand, and Lower figure shows one attached on left hand.

The system architecture is shown in Fig. 2. As the first trial, a small humanoid robot "HRP-2m" is used for safety as a control target that is a substitution of the patient and the assistive system in the practical situation. The desired trajectory of each joint is transmitted from the wearable controller to the HRP-2m by TCP/IP.

B. Wearable walk controller

A pair of wearable walk controllers shown in Fig. 3 is developed to convey a wearer's intention to the walking support system intuitively. The potentiometer is attached on the distal interphalangeal (DIP), proximal interphalangeal (PIP) and metacarpophalangeal (MP) joint of each controller and two potentiometers are installed to an controller's wrist joint to measure flexion/extension and ulnar deviation/radial deviation. This study does not use flexion/extension and ulnar deviation/radial deviation to control the assistive system. A two-dimensional gyro sensor is attached on the wrist joint of a right-hand controller to measure pronation and supination of a right arm. Specifications of the controller is on Table I.

A patient wears a pair of the controllers on his/her hands and swings both his/her index fingers as to simulating foot motions of his/her walking. The amplitude and period of the swing corresponds to a step length and period of the walk, respectively. The pronation/supination angular velocity

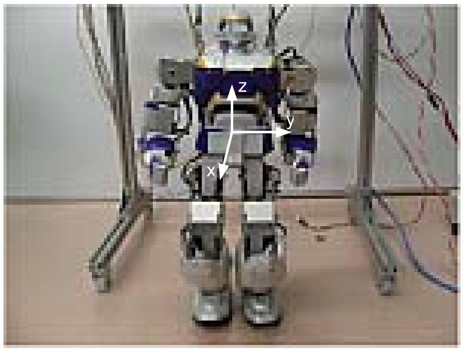


Fig. 4. Humanoid robot "HRP-2m"

of the wrist joint of his/her right arm corresponds to a walk direction. The cooperative control algorithm based on a cart-table model designs trajectories of each joint for stable walking pattern that satisfies the intention expressed by the wearer's hand motion. If the controller measures pronation/supination of the right forearm before it starts a step, a rotation action to change the walk direction is added to the step.

TABLE I

SPECIFICATIONS OF WEARABLE WALK CONTROLLERS

Size	106x100x60[mm]
Weight	175[g]×2
Joint	10(right and left hand)
Sensor	Potentiometer ×10 and Gyro ×1(right hand)
Sensing frequency	500Hz

C. *Small humanoid robot*

The performance of the walking support system should be investigated by applying it to a patient in the final stage of a developing process. Experimental settings may be adjusted according to the progress and the purpose of the study from viewpoint of risk of an accident, a preparation cost and an experiment cost. This study uses a small humanoid robot "HRP-2m" [14] shown in Fig. 4 as a substitute of an assistive system including a patient in order to investigate our proposed cooperative control algorithm. The specifications of HRP-2m is on TABLE II.

TABLE II

SPECIFICATIONS OF HRP-2M

Name	HRP-2m Choromet
Height	37[cm]
Weight	1.5[kg]
DOF of both Legs	12
OS	ART-LINUX

III. WALK PARAMETER EXTRACTION FROM FINGER SWING

A. *Step length*

The step length is determined by the relative angle between two legs, while the relative angle of the hip joint between the leg and the torso of the robot should be determined from viewpoint of the robot stability. The step length is therefore directly proportional to difference of MP joint angles of two index fingers at the moment that a MP joint angle on the swing leg side becomes the maximum. The absolute angle of the hip joints of the robot is determined by the trajectory of the COM.

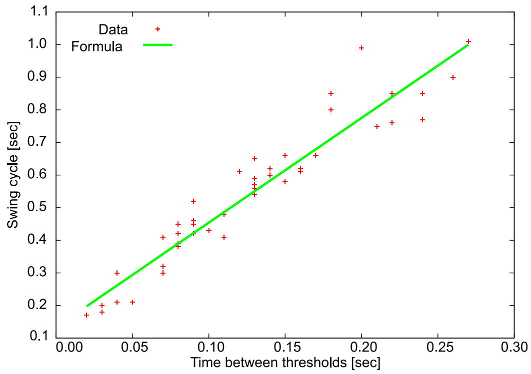


Fig. 5. Relationship between cycle of swinging finger and time between two thresholds of bending ratio

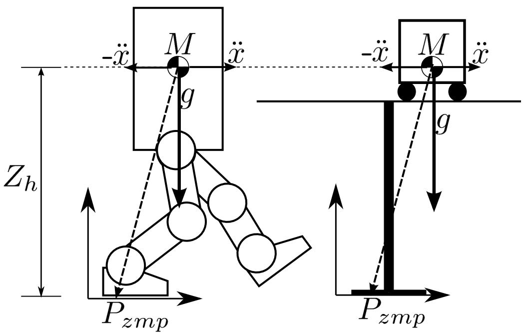


Fig. 6. Simplification the model of a humanoid robot with a Cart-table model. Z_h is the height of COM, p_{zmp} is the position of ZMP, x is the position of COM, M is the mass, g is the acceleration of gravity.

B. *Walking period*

Walking period is determined by the swing period of the finger. However the swing period can be obtained after the swing is completed. In order to predict the walking period, we suppose that the period is proportion to a transit time through a partial range of the finger swing angle. We confirm that this supposition is reasonable in experiment as shown in fig. 5.

The relationship is expressed by eq.(1). The parameters of this equation are obtained based on the experimental data by using least-square method.

$$Cycle = a \times Time + b, \tag{1}$$

where

$$\begin{aligned} a &= 3.8 \quad and & (2) \\ b &= 0.15. & (3) \end{aligned}$$

C. *Turning walking direction*

A gyro sensor is attached on the wrist joint of the right forearm so that an angular velocity of supination/pronation of the right forearm could be measured. Once large velocity of supination/pronation is measured during the double support phase, the robot adds a rotation action to a swing leg to change the walk direction.

IV. COOPERATIVE WALK CONTROL

A. *Cart-table model*

A cart-table model[11] is a simplified model of complicated robot dynamics by assimilating center of mass (COM) of a robot with a cart on a table. It saves a calculation cost that is an important factor for a realtime control in a limited calculation capacity. The cart-table model can be expressed by

$$\ddot{x}(t) = \frac{g}{z_h}(x(t) - p_x(t)), \tag{4}$$

where x is position of the COM, z_h is height of the COM, p is the position of zero moment point (ZMP), and g is gravitational acceleration.

$x(t)$ is rewritten in discrete formula with the sampling time Δt as follows,

$$\ddot{x}_i = \frac{x_{i-1} - 2x_i + x_{i+1}}{\Delta t^2}. \tag{5}$$

$p_x(t)$ is derived by using eq.(4) and (5).

$$\begin{aligned} p_i &= a_i x_{i-1} + b_i x_i + c_i x_{i+1} && (6)\\ a_i &= -\frac{Z_h}{g\Delta t^2} && (7)\\ b_i &= \frac{2Z_h}{g\Delta t^2} + 1 && (8)\\ c_i &= -\frac{Z_h}{g\Delta t^2} && (9) \end{aligned}$$

Equation (6) is rewritten in matrix formula as follows,

$$\boldsymbol{x} = A^{-1}\boldsymbol{p_x}, \tag{10}$$

where

$$\boldsymbol{p_x} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_{N-1} \\ p_N \end{bmatrix}, \boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{N-1} \\ x_N \end{bmatrix} \tag{11}$$

$$A = \begin{bmatrix} a_1 + b_1 & c_1 & 0 & & \\ a_2 & b_2 & c_2 & & \\ & & \ddots & & \\ & & a_{N-1} & b_{N-1} & c_{N-1} \\ & & 0 & a_N & b_N + c_N \end{bmatrix}. \tag{12}$$

These equations (10)–(12) express a motion in a sagittal plain. In the same way, a motion in a lateral plain can be expressed by

$$\boldsymbol{y} = A^{-1}\boldsymbol{p_y}. \tag{13}$$

.

Equation (10) expresses a relation between a trajectory of the ZMP and a trajectory of the COM for a length of time. The desired COM trajectory for a stable walking is therefore calculated from the ZMP trajectory. A stability of a walking is ensured if the ZMP is located in a supporting polygon.

It is necessary to enlarge the size of the matrix for ensuring stability of walking for a long time. A large size of the matrix causes delay of a robot response due to a lot of calculation. This delay becomes a crucial problem because synchronization between a wearer's operation and a robot motion is important. This paper therefore proposes an algorithm that ensures stability of walking during a period of step and has short delay enough to synchronize wearer's operation and robot's motion.

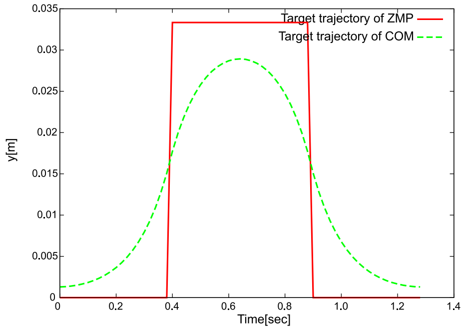


Fig. 7. Target trajectories of ZMP and COM in y-axis direction in one step

B. *One-step walking mode*

1) Definition of walk phase: The joint trajectory in one step can be assumed to be independent of others since the robot motion is paused at the middle of a double support phase. A terminal position of the trajectory becomes an initial position of the next step. A step of a biped walk in this paper is divided into three phases.

- Preparation phase: A velocity of COM of the robot increases from zero to the target velocity in order to lift a swing leg. Both legs are supporting its weight at this phase. The initial posture of the robot is the same as the posture at the end of the previous step. That is the initial position of the COM is located at the middle point of two feet.
- Walking phase: This phase starts when the swing leg leaves the ground and then it ends when the swing leg lands.
- Return phase: This phase starts when the swing leg lands. At this moment, the COM has a velocity and the velocity decreases and then the position of the COM is finally located at the middle point of two feet.

2) Design of trajectory in each phase: The robot designs a ZMP trajectory for only one step when the wearer starts bending PIP and DIP joints of his index finger. If there is no operation from the wearer, the robot keeps the position of the COM in a supporting polygon. A leg of the two legs on the side of the bending finger becomes the swing leg. The trajectory design strategies in three phases are separately explained.

- Preparation phase: The target ZMP is designed at a center of both feet. The velocity of the COM is accelerated enough to follow the target COM trajectory. The target trajectory of the COM is derived by eqs. (10) and (13) based on the target ZMP. The target trajectory of ZMP and COM in y-axis are shown in Fig. 7.

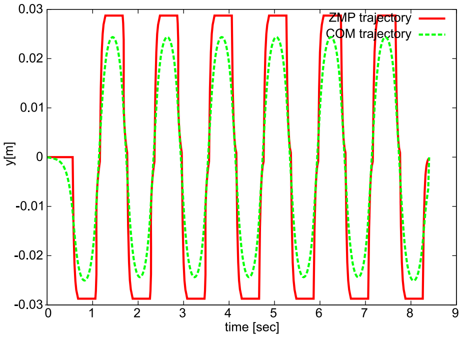


Fig. 8. Trajectories of ZMP and COM in y-axis direction in continuous walking mode

- Walking phase: The target ZMP is fixed at the foot position of the supporting leg. The velocity of the COM is accelerated to follow the target COM trajectory that is derived by eqs. (10) and (13) based on the target ZMP. A free leg lifts and lands at the target step length that is proportional to an angular difference between MP joint angles of left and right hands.
- Return phase: The target ZMP is designed at a center of both feet. The velocity of the COM is decelerated to follow the target COM trajectory that is derived by eqs. (10) and (13) based on the target ZMP.

The calculation for one step is finished within 20[msec] since the size of the matrix is limited just to cover one step. The biped walk starts immediately after the calculation. When the walking period is shorter than 0.2[s], the walking period is set 0.2[s]. When the walking period is longer than 0.8[s], the walking period is set 0.8[s].

C. *Continuous walking mode*

In the one-step walking mode, the wearer must keep swinging his finger for each step. However, it is tired and boring work when he walks for a long distance.

For such a situation, the robot keeps walking without the finger swing when the following three conditions are satisfied. 1) The walking period indicated by the finger swing is shorter than 0.3[sec]. 2) The interval time from previous input to the next input is shorter than 0.1[sec]. 3) At least one of two fingers keeps bending. When the wearer stretches both index fingers, it stops walking. The walk parameters such as the step length and the walking period are fixed to the walk parameters just before the continuous walk.

The trajectory of COM for the continuous walking is calculated by using the trajectory of ZMP which is updated at each 20[msec] for the following walk until the robot receives the signal of walking stop.

V. EXPERIMENTS

A. *Temporal synchronization of human operation and system assistance*

The preparation phase starts when the bending ratio of one of two index fingers exceeds a threshold at 20%. The bending ratio r is calculated by

$$r = 100\frac{l_f - l(t)}{l_f}, \tag{14}$$

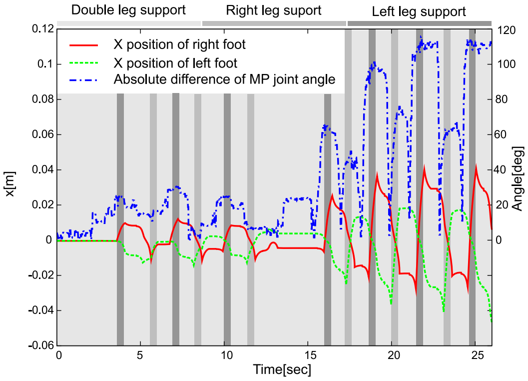


Fig. 9. Swing motion and step length. The step length increases as the absolute difference of MP joint angles increases.

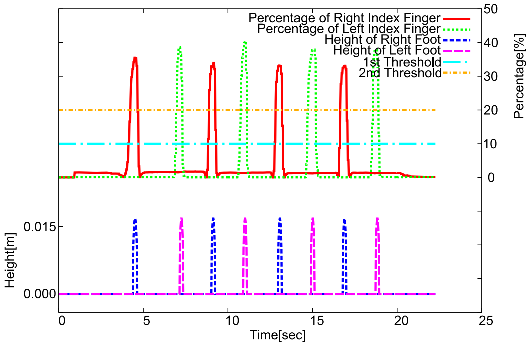


Fig. 10. Temporal synchronization of human operation and system assistance. The robot starts the preparation phase after the bending ratio exceeds 20%. It however takes 100 [msec] for a leg to start swing due to the preparation phase.

where l_f is a full length of an index finger, and $l(t)$ is length of the flexing index finger at time t. Figure 10 shows the bending ratio and heights of two feet from a ground.

B. *Variable step length*

Table III shows the period of each phase. The walk velocity is variable by changing a step length. The absolute difference of angles between both MP joints and step length are shown in Fig. 9. As the absolute difference increases step by step, the step length that is the position difference between right foot and left foot also increases.

TABLE III

PERIOD OF EACH PHASE IN ONE STEP

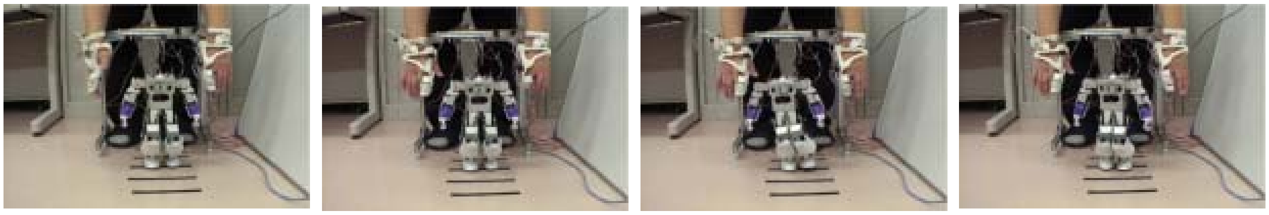
Phase	One-step	Continuous
Preparation phase	0.1[sec]	0.0[sec]
Walking phase	0.2 – 0.8[sec]	0.4[sec]
Return phase	0.1[sec]	0.0[sec]

C. *Walking direction change*

The angular velocity of the right forearm and change of a walking direction are shown in Fig. 11. Once a velocity of supination/pronation exceeds about 300 [deg/sec] during the double support phase, the walking direction for a next step is determined. The robot changes its direction at about the 20 degree in the same direction of the forearm rotation during the next single support phase. After finishing the single support phase, the walking direction for a next step is reset to neutral.

1st Step 2nd Step 3rd Step 4th Step

Fig. 12. Straight walk with various step lengths



(a) Walking direction set by right forearm's supination (b) Flexion of index finger of left hand (c) COM Shift to right side for 1st rotation (d) 1st rotation (Left leg has just landed.)

Fig. 13. Change of walking direction

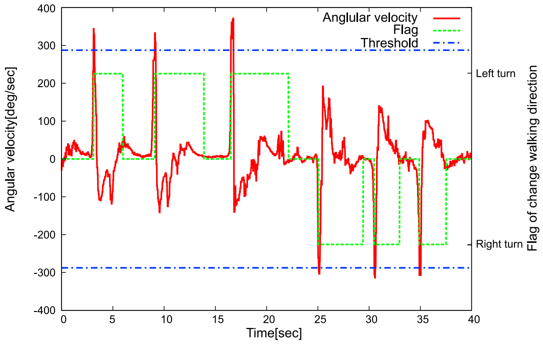


Fig. 11. Angular velocity and change of walking direction

VI. CONCLUSIONS AND FUTURE WORKS

This paper proposed a cooperative control algorithm that designs a stable biped walk satisfying a wearer's intentions relating to his walk. At first, a pair of controllers with several DOFs has been developed to convey a wearer's intention to the walking support system. The amplitude and period of the finger swing corresponds to a step length and period of the walk. The pronation/supination angle of the wrist joint of his/her right arm corresponds to a walk direction. The cooperative control algorithm based on a cart-table model designs trajectories of each joint of the humanoid robot for stable walking pattern that satisfies a step length, walking period and walk direction expressed by the wearer's hand motion. The designed walking pattern is executed in realtime by the humanoid robot. Our proposed algorithm enables the humanoid robot to start and stop stable walk with variable step length and walking period and to change the walking direction according to operator's intentions.

As the final goal of our study is that an exoskeletal walking support system could provide a comfortable support to a paraplegia patient. Before applying this cooperative control algorithm to an assistive system with a patient, a stability of the assistive system should be improved against an unexpected disturbance.

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