

# A Lower-Limb Power-Assist Robot with Perception-Assist

Yoshiaki Hayashi

Dept. Advanced Technology Fusion,  
Saga University, Saga, Japan  
hayashi@me.saga-u.ac.jp

Kazuo Kiguchi

Dept. Advanced Technology Fusion,  
Saga University, Saga, Japan  
kiguchi@ieee.org

**Abstract**— In order to assist the motion in the daily lives of physically weak persons such as elderly persons, many kinds of power-assist robots have been developed. In the case of some physically weak persons, the ability to perceive the environment is sometimes deteriorated also. A method of perception-assist has been proposed to assist not only the user's motion but also the user's interaction with an environment, by applying the modification force to the user's motion if it is necessary. In this paper, the perception-assist for a lower-limb power-assist exoskeleton robot is proposed. In the daily life, the walking is very important for persons to achieve desired tasks. Basically, the robot assists the user's muscle force according to the user's motion intention which is estimated based on EMG signals. If the robot has found problems which might lead the user to dangerous situation such as the falling down, the robot tries to modify the user's motion in addition to the ordinal power-assists to make the user walk properly. Since the user might fall down by the effect of the additional modification force of the perception-assist, the robot automatically prevents the user from falling down by considering ZMP (Zero Moment Point). The effectiveness of the proposed method has been evaluated by performing experiments.

**Keywords**- perception-assist, full prevention, power-assist.

## I. INTRODUCTION

Some persons have difficulties in living an independent life because of a disease or a decline of muscle force. Power-assist robots are useful to help physically weak persons such as elderly persons live an independent life and are also expected to be applied to various fields [1]-[15]. In the power-assist robots for physically weak persons, it is important to assist the user's motion automatically according to the user's intention. The power-assist robots are able to estimate the user's motion intention based on bio-logical signals like electromyogram (EMG) [7, 8]. However, in the case of some elderly or physically weak persons whose motor ability is deteriorated, the ability to perceive the environment is sometimes deteriorated also. In such case, even though the user expands the motor activity range by using the power-assist robot, the user might not be able to perceive the risks associated with their own motions correctly and be involved in an unexpected accident. Therefore, it is sometimes necessary for the power-assist robot to have the ability of the perception-assist as well as the ability of the ordinary power-assist. The power-assist robot with perception-assist has been proposed to keep

monitoring the interaction between the user and the environment using its own sensors, and tries to modify the user's motion automatically by adding additional force only if any problems are found in the user's motion. For example, in the case of upper-limb power-assist robots, the user achieves tasks using various tools. If the robot judges the tool motion is wrong or dangerous, the robot automatically tries to modify the tool motion by adding additional force to the user's hand [16]-[20]. In the perception-assist, sensors such as stereo cameras and/or laser range finders are necessary to monitor the interaction between the user and the environment.

In this paper, the perception-assist for a lower-limb power-assist exoskeleton robot is proposed to make elderly and/or physically weak persons walk properly and safely in a daily living environment. If a person whose ability to perceive the environment is deteriorated misidentifies a bump, the person might stumble on the bump and fall down because of the spatial misconception, which could result in serious damage. To prevent a user away from an unexpected accident, the proposed power-assist robot observes the interaction between the user and the environment in front of the user and modifies the user's motion as necessary by adding the modification force automatically, although the robot always performs the ordinary power-assist normally as well. However, the user might lose his/her balance and fall down by the effect of the additional modification force of the perception-assist because it is automatically generated regardless of the user's motion intention. Consequently, the perception-assist is carried out considering ZMP (Zero Moment Point) [21] to keep stable walking in the proposed method.

In this study, the proposed perception-assist method is applied to a 2DOF lower-limb power-assist exoskeleton robot and the effectiveness of the proposed method is evaluated by performing experiments.

## II. LOWER-LIMB POWER-ASSIST ROBOT

The lower-limb power-assist exoskeleton robot used in this study is shown in Fig. 1. Each limb of the robot consists of two DC motors with encoders to measure the hip and knee joint angles, An encoder to measure the ankle joint angle, two tactile switches in the heel and the toe to know whether the sole contacts with the ground, links for thigh and shank, and a foot holder. The robot is attached to the torso, thigh, shank, and foot

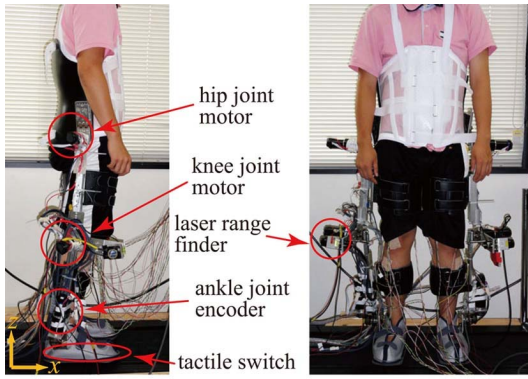


Fig. 1 Lower-limb power-assist exoskeleton robot.

Table I Range of motions of lower limb

Type of motion	Human [deg]	robot [deg]
Hip flexion	130	120
Hip extension	30	20
Knee flexion	140	110
Knee extension	0	0

of the user. Hip flexion/extension motion and knee flexion/extension motion of the user can be assisted by the robot. The range of motion of each joint is shown in Table I. As shown in Table I, the range of motion of each joint of the robot is slightly smaller than the physiological range of motion in order to ensure the safety.

The laser range finder (URG-04LX, HOKUYO AUTOMATIC CO., LTD.) is attached near the knee joint of the robot. In addition, the encoder is installed to measure the rotation of the axis of the laser range finder. The laser range finder is used to recognize the environment in front of the user in  $x$ - $z$  plane as shown in Fig. 1.

### III. POWER-ASSIST

The controller of the robot consists of the power-assist part and the perception-assist part. Each motor torque is the sum of calculated torques in each part. In this section, the power-assist part is explained in detail.

The skin surface electromyogram (EMG) is used to predict the user's motion intention and assist the user's motion in real-time in accordance with the user's motion intention, since it directly reflects the user's motion intention [7]. Seven channels of EMG signals per leg are measured and used as input signals to the robot. Each channel mainly corresponds to one muscle. The locations of EMG electrodes are shown in Fig. 2. Since the raw EMG signal is not suitable for the control input, a feature of the EMG signal is extracted. We chose to use the Root Mean Square (RMS). The RMS calculation is written as

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^N v_i^2} \quad (1)$$

where  $N$  is the number of samples in a segment,  $v_i$  is the voltage at  $i^{\text{th}}$  sampling point. The number of samples  $N$  is set to be 300 and the sampling time is 500 $\mu$ sec (the sampling frequency is 2 kHz) in this study. The relationship between the seven RMS values and the generated vector of joint torques is implemented as shown in eq. (2).

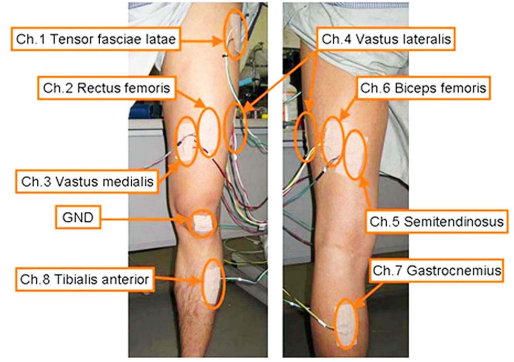


Fig. 2 Location of the EMG Electrodes.

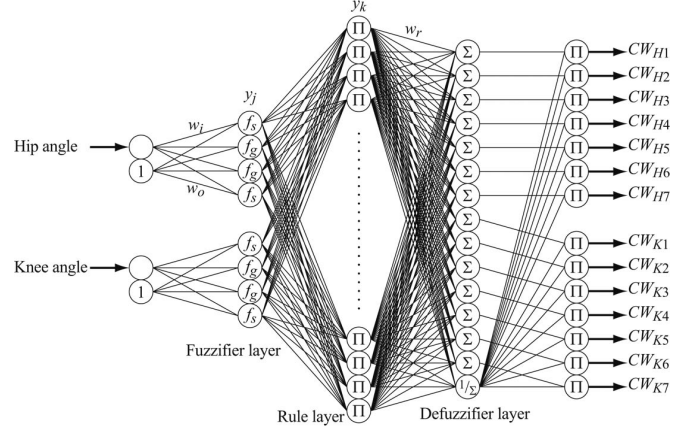


Fig. 3 Fuzzy-Neuro Modifier.

$$\begin{bmatrix} \tau_{h,pow} \\ \tau_{k,pow} \end{bmatrix} = \begin{bmatrix} w_{h1} & w_{h2} & \cdots & w_{h6} & w_{h7} \\ w_{k1} & w_{k2} & \cdots & w_{k6} & w_{k7} \end{bmatrix} \begin{bmatrix} ch_1 \\ ch_2 \\ \vdots \\ ch_6 \\ ch_7 \end{bmatrix} \quad (2)$$

where  $\tau_{h,pow}$  and  $\tau_{k,pow}$  are torques for hip flexion/extension and knee flexion/extension, respectively.  $ch_j$  represents the RMS value of the EMG signal measured in channel  $i$ .  $w_{hj}$  is the weight value for  $j^{\text{th}}$  EMG signal to estimate the hip flexion/extension motion and  $w_{kj}$  is the weight value for  $j^{\text{th}}$  EMG signal to estimate the knee flexion/extension motion. The relationship between each joint torque and the RMS values of the EMG signals is changed depending on the user's lower-limb posture. Therefore, the weights of the matrix in eq. (2) are adjusted in real time according to the user's lower-limb posture by using a neuro-fuzzy modifier which is shown in Fig. 3 [7]. This adaptation technique with neuro-fuzzy modifier enables the controller to adjust itself to be suitable for any posture of any person.  $w_{hj}$  and  $w_{kj}$  are adjusted as follows by using neuro-fuzzy modifier as shown in Fig. 3.

$$\begin{aligned} w_{hj} &= w_{h0,j} \times CW_{Hj} \\ w_{kj} &= w_{k0,j} \times CW_{Kj} \end{aligned} \quad (3)$$

where  $w_{h0j}$  and  $w_{k0j}$  are the initial weight values.  $CW_{Hj}$  and  $CW_{Kj}$  are changed according to the user's lower-limb posture in order to adjust the relationship between each joint torque and the RMS values.

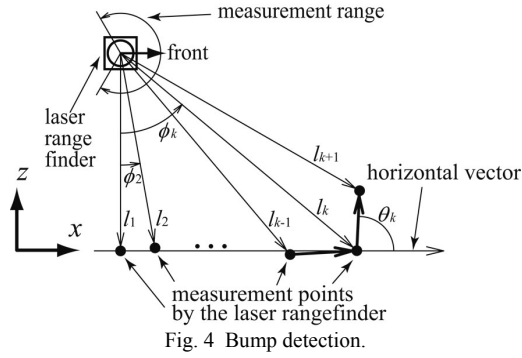


Fig. 4 Bump detection.

#### IV. PERCEPTION-ASSIST

In the perception-assist part, the robot judges whether the user's motion is in danger at first. The user is able to move his/her body according to his/her motion intention by the assist of the robot. However, if the user has problems in his/her ability to perceive the environment, the user might not be able to recognize the danger of own motion correctly. Therefore, if the robot judges the user's motion is dangerous, the robot needs to modify the user's motion automatically. In order to realize the perception-assist, the robot is required to understand not only the motion of the user but also the interaction between the user and the surrounding environment. In the case of lower-limb power-assist robots, the robot needs to prevent the user from falling down during walking, ascending, descending, or standing up. Specifically, a user who has problems in the ability to perceive the environment might overlook or misunderstand a bump and stumble on it. Although a healthy person might be able to recover the own balance, a user who needs the help of the power-assist robot might fall down. For this reason, the robot needs to be careful with the user's interaction with the environment.

In this paper, the robot detects bumps and prevents the user from falling down and stumbling by the perception-assist during walking. However, although the robot tries to modify the user's motion in addition to the ordinary power-assists to walk properly, the motion modification is automatically generated regardless of the user's intention. For this reason, the user might lose his/her balance and fall down by the effect of the additional modification force of the perception-assist. To prevent such case, the robot takes into account ZMP in the perception-assist algorithm.

##### A. Environmental sensing

The laser range finder is used to recognize the environment in front of the user. A bump in front of the user is detected by the laser range finder and the distances from the user's toe to the bump and the height of the bump are calculated. The robot is careful with the user's motion so that the user does not stumble on the bump.

The measured points from the laser range finder are shown in Fig. 4. As shown in Fig. 4, each vector is calculated based on these adjacent measured points. Then,  $\theta_k$  which is the angle between these vectors and the horizontal vector can be calculated. The robot estimates whether there is a bump or not based on  $\theta_k$ . When the absolute value of  $\theta_k$  is small enough, the

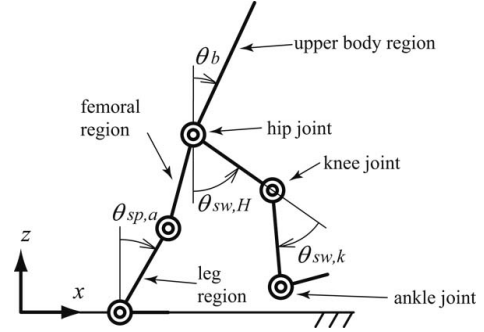


Fig. 5 User posture.

robot judges that the ground is flat. On the other hand, when the absolute value of  $\theta_k$  is large enough, the robot judges that there is a bump in front of the robot. When the absolute value of  $\theta_k$  is middle, the robot judges that the ground is slope. These threshold values are defined experimentally. If the robot detects a bump, the distance from the user's toe to the bump and the height of the bump are recorded. The scanning time and the angular resolution of the laser range finder are 80 msec and 0.36 deg, respectively.

##### B. ZMP

In order to prevent the user from losing his/her balance and falling down by the effect of the additional modification force by the perception-assist which is given regardless of the user's intention, the robot takes into account ZMP. The user's body is modeled as shown in Fig. 5. The supporting leg is found by tactile switches located in both soles. Then, the posture of the user's body region is calculated using the joint angles of the supporting leg as follows.

$$\theta_b = \theta_{sp,h} - \theta_{sp,k} + \theta_{sp,a} \quad (7)$$

where  $\theta_b$  is the angle of upper body region,  $\theta_{sp,h}$ ,  $\theta_{sp,k}$  and  $\theta_{sp,a}$  are the angles of hip, knee and ankle joint of the support leg, respectively.  $\theta_{sw,h}$ ,  $\theta_{sw,k}$  and  $\theta_{sw,a}$  are the angles of hip, knee and ankle joint of the swing leg. The positions of each joint are calculated as follows

$$\begin{cases} x_{sp,k} = L_l \sin \theta_{sp,a} \\ z_{sp,k} = L_l \cos \theta_{sp,a} \end{cases} \quad (8)$$

$$\begin{cases} x_h = x_{sp,k} - L_f \sin \theta_{sp,H} \\ z_h = z_{sp,k} + L_f \cos \theta_{sp,H} \end{cases} \quad (9)$$

$$\begin{cases} x_{sw,k} = x_h + L_f \sin \theta_{sw,H} \\ z_{sw,k} = z_h - L_f \cos \theta_{sw,H} \end{cases} \quad (10)$$

$$\begin{cases} x_{sw,a} = x_{sw,k} + L_l \sin(\theta_{sw,H} - \theta_{sw,k}) \\ z_{sw,a} = z_{sw,k} - L_l \cos(\theta_{sw,H} - \theta_{sw,k}) \end{cases} \quad (11)$$

where  $L_l$  and  $L_f$  are the lengths of the shank region and the femoral region, respectively.  $x$  and  $z$  are the positions of each joint. The  $sp$  represents the supporting leg,  $sw$  represents the swing leg,  $a$ ,  $k$  and  $h$  represent ankle, knee and hip joint, respectively. In addition,  $\theta_{sp,H} = \theta_{sp,h} - \theta_b$ ,  $\theta_{sw,H} = \theta_{sw,h} - \theta_b$ . The positions and accelerations of the center of gravity (COG) of upper body, thigh and shank are calculated from (7) to (11). ZMP is calculated is written as

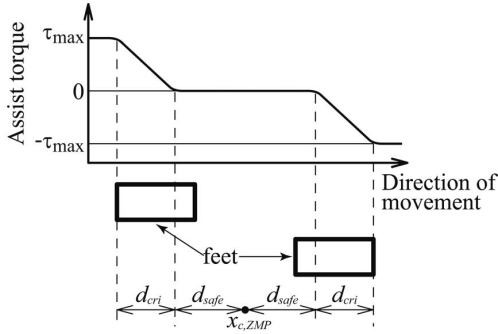


Fig. 6 Perception-assist area based on ZMP.

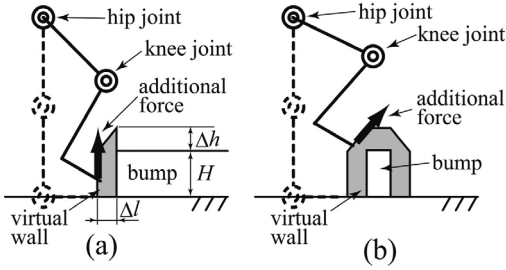


Fig. 7 Virtual wall area.

$$x_{zmp} = \frac{\sum_{i=1}^n m_i (\ddot{z}_i + g) x_i - \sum_{i=1}^n m_i \ddot{x}_i z_i}{\sum_{i=1}^n m_i (\ddot{z}_i + g)} \quad (12)$$

where  $x_{zmp}$  is the coordinate of ZMP in the horizontal direction,  $m_i$  is the mass of each human body part and robot,  $x_i$  is the position of the COG of each part in the horizontal direction,  $z_i$  is the position of the COG of each part in the vertical direction and  $g$  is the acceleration of gravity. The weight and the position of the COG of each body part are decided based on [22]. The perception-assist is performed considering  $x_{zmp}$ .

### C. Fall prevention assist

The robot performs fall prevention assist based on the results of environmental sensing and calculated ZMP.

When the robot estimates there is no bump in front of the user, the robot evaluates the user's walking based on  $x_{zmp}$  in order to prevent the user from falling down in addition to the ordinary power-assist. If  $x_{zmp}$  is located in an undesired area, the robot automatically generates additional hip joint torque to change the location of  $x_{zmp}$  to the safe area by activating the upper body of the user. The area in which the robot generates the additional hip joint torque in addition to the power-assist is defined as shown in Fig. 6 so that  $x_{zmp}$  is moved to center of the support polygon. Because the mass of the upper body region is larger than other regions and the movement of the mass of the upper body is the most effective way to change ZMP, the additional hip joint torque (i.e., the perception-assist torque) is generated at the hip joint motor of the support leg. In Fig. 6,  $\tau_{max}$  is the amount of the maximum hip joint torque which is defined to protect the user from the injury. The perception-assist torque for walking-assist is calculated using eq. (13).

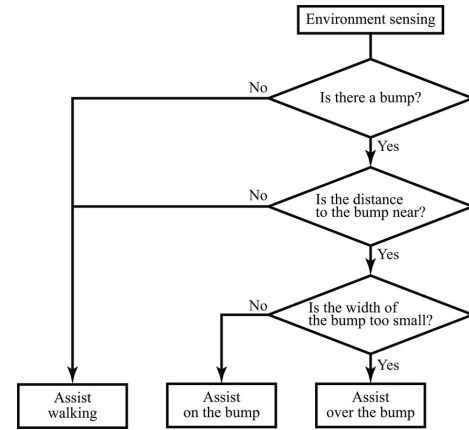


Fig. 8 Flowchart of perception-assist.

$$\tau_{walk} = \begin{cases} 0, & (|\Delta x_{zmp}| < d_{safe}) \\ \frac{\tau_{max}}{d_{cri}} (\Delta x_{zmp} - Sgn \times d_{safe}), & (d_{safe} \leq |\Delta x_{zmp}| \leq d_{safe} + d_{cri}) \\ Sgn \times \tau_{max}, & (|\Delta x_{zmp}| \leq d_{safe} + d_{cri}) \end{cases} \quad (13)$$

$$\begin{aligned} \Delta x_{zmp} &= x_{c,ZMP} - x_{zmp} \\ Sgn &= \text{sgn}(\Delta x_{zmp}) \end{aligned}$$

where  $x_{c,ZMP}$  is the center position of the support polygon,  $d_{safe}$  and  $d_{cri}$  are shown in Fig. 6.  $\tau_{max}$ ,  $d_{safe}$  and  $d_{cri}$  are experimentally defined.

When the robot detects a bump, a virtual wall area is generated in front of the bump as shown in Fig. 7(a). It assumes that the first point which is judged as a bump by the environmental sensing is the origin. The virtual wall area is shown by the trapezoid represented by  $\Delta l$ ,  $\Delta h$  and  $H$  in Fig. 7 (a). Here,  $H$  means the height of the bump,  $\Delta l$ ,  $\Delta h$  are the experimentally defined parameters as shown in Fig. 7(a). In the experiments to define  $\Delta l$  and  $\Delta h$ , some subjects walk at normal speed (about 1.4m/sec) [23]. Then, we defined  $\Delta l$  and  $\Delta h$  as minimum values in which the subjects could overcome the bump. The location of the toe of the user's swing leg is calculated using eq. (11). If the user's foot enters the virtual wall area as shown in Fig. 7(a), the robot judges the user might stumble on the bump and generates the additional motion modification force along the virtual wall in addition to the power-assist force to avoid the collision with the bump. The additional motor torque generated by the effect of the additional motion modification force (i.e., the perception-assist torque) is written as follows.

$$\begin{bmatrix} \tau_{h,add} \\ \tau_{k,add} \end{bmatrix} = \mathbf{J}^{-T} \mathbf{f}_{add} \quad (14)$$

where  $\tau_{h,add}$  is the additional hip joint torque,  $\tau_{k,add}$  is the additional knee joint torque,  $\mathbf{J}$  is Jacobian matrix and  $\mathbf{f}_{add}$  is the additional motion modification force generated along the virtual wall. The amount of  $\mathbf{f}_{add}$  is related with  $\Delta l$  and  $\Delta h$ . The amount of  $\mathbf{f}_{add}$  was defined based on the change of ZMP and the feeling of the subjects at the same time when  $\Delta l$  and  $\Delta h$  are defined. Note that  $\tau_{h,add}$  and  $\tau_{k,add}$  are generated without the user's intention. Therefore, another hip joint torque must be

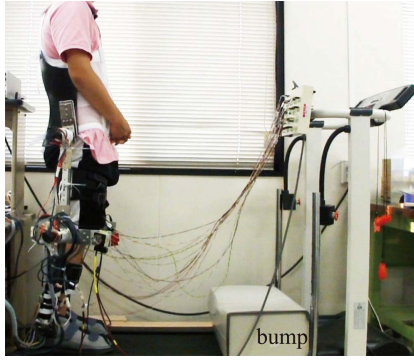


Fig. 9 Experimental condition.

added to cancel the undesired effect of the ZMP change caused by the additional force so that the user does not lose his/her balance and fall down by the effect of the perception-assist. Based on eq. (12),  $\tau_{cancel}$  which is the torque to cancel the effect of the change of ZMP is calculated as follows.

$$f_{body} = \frac{\tau_{h,add}}{d_{l,cog}} \cdot \frac{x_{l,cog} \sin \theta_{sw,H} - z_{l,cog} \cos \theta_{sw,H}}{x_{b,cog} \sin \theta_b - z_{b,cog} \cos \theta_b} \quad (15)$$

$$\frac{\tau_{k,add}}{d_{l,cog}} \cdot \frac{x_{l,cog} \sin(\theta_{sw,k} - \theta_{sw,H}) + z_{l,cog} \cos(\theta_{sw,k} - \theta_{sw,H})}{x_{b,cog} \sin \theta_b - z_{b,cog} \cos \theta_b}$$

$$\tau_{cancel} = f_{body} \times d_{b,cog} \quad (16)$$

where  $d_{l,cog}$  is the length between hip joint and the COG of the femoral part,  $d_{l,cog}$  is the length between knee joint and the COG of the leg part and  $d_{b,cog}$  are the length between hip joint and the COG of the body part.  $x_{p,cog}$  and  $z_{p,cog}$  are the position of each body part ( $p=t$ :femoral part,  $l$ :leg part,  $b$ :body part).

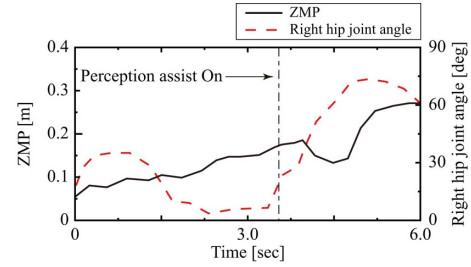
After the user's foot is lifted over the bump, the robot estimates whether the top surface of the bump has enough space to place the user's foot on it. If the top surface of the bump has enough space to place the user's foot on it, the robot takes the additional perception-assist torque away from the user and performs the normal power-assist. In the case that the top surface of the bump is too narrow, if the robot recognizes the ground ahead on the bump, the robot performs another perception-assist to overcome the bump as shown in Fig. 7(b). Meanwhile, if the robot cannot recognize the ground ahead on the bump, the robot tries to turn back the user's foot because the robot cannot find the space to place the user's foot on it safely. Thus, the robot takes into account ZMP to prevent the user from losing his/her balance and falling down in any case.

The flowchart of the perception-assist is shown in Fig. 8. The robot performs the perception-assist in accordance with the flowchart shown in Fig. 8 in addition to the power-assist represented in eq. (2).

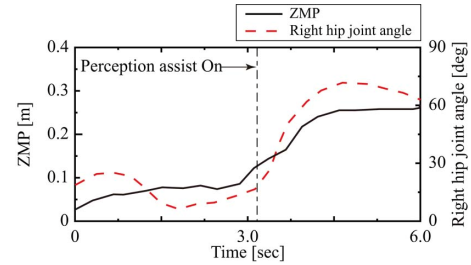
## V. EXPERIMENTS

In order to verify the effectiveness of the proposed method, experiments were carried out. In the experiments, a young male subject walked on the treadmill as shown in Fig. 9.

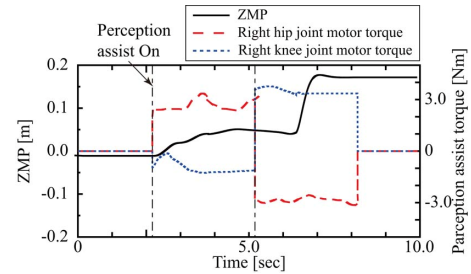
For the first experiments, a bump (width of about 300mm, height of about 200mm) was prepared in front of the subject.



(a) ZMP when the robot generated the perception-assist force without taking into account ZMP (bump : width of about 300mm, height of about 200mm )



(b) ZMP when the robot generated the perception-assist force with taking into account ZMP (bump : width of about 300mm, height of about 200mm )



(c) ZMP and joint torques when the robot generated the perception-assist force with taking into account ZMP (bump : width of about 30mm, height of about 40mm )

Fig. 10 Experimental results.

After the subject walked on the treadmill 10 seconds, the subject moved his foot to stumble on the bump on purpose in order to verify the effectiveness of the proposed method. The robot generates the perception-assist torque to prevent the subject from stumbling on the bump when the subject's foot enters in the virtual wall area. In the experiments, the robot did not generate the perception-assist force during 10 seconds from the beginning.

The experimental result with the perception-assist force without taking into account ZMP is shown in Fig. 10(a) and that with taking into account ZMP is shown in Fig. 10(b). In the both cases, the subject was able to place his foot on the bump without stumbling. However, in the case of Fig. 10(a) in which the robot assisted the subject without taking into account ZMP, the subject lost his balance by the unintended additional force from the perception-assist, and ZMP moved backward opposite to the direction of movement at 4-5 seconds. Meanwhile, in the case of Fig. 10(b) in which the robot assisted the subject with taking into account ZMP, the subject kept his balance even though there was the additional force from the perception-assist, and ZMP was stable. In the experiments, the robot generated larger additional force by the perception-assist than usual ( $f_{add}$  which was defined experimentally) in order to

verify the effectiveness of the proposed method because the subject was a young healthy male as remarked above.

For the second experiments, another bump (width of about 30mm, height of about 40mm) was prepared in front of the subject. This bump was narrower and lower than the bump in the first experiments. The first experiment situation is the case that the user cannot lift up his foot up to a height of a bump although the user can recognize the bump. The second experiment situation is the case that the user might not be able to recognize a bump because the bump is small. In this experiment, after the subject walked on the treadmill 10 seconds, the subject placed the right foot on the bump on purpose. Although the subject stepped on the bump during walking, the robot avoided it by the additional force by the perception-assist. Also in these experiments, the robot did not generate the perception-assist torque during 10 seconds from the beginning.

The experimental result is shown in Fig. 10(c). In this case, the robot recognized the bump at about 2 seconds, and then generated the perception-assist force to lift up the subject's foot. In addition, the robot recognized the width of the bump is narrow to place the foot on it after about 5 seconds, and then the robot generated the another additional force so that the subject stepped over the bump. During the experiments, the robot took into account ZMP to prevent the subject from falling down. These experimental results show that the proposed perception-assist with taking into account ZMP can prevent the user from falling down.

## VI. CONCLUSION

In this paper, the perception-assist for a lower-limb power-assist exoskeleton robot is proposed to assist the walking of the elderly or physically weak persons. In the proposed perception-assist, the power-assist robot observes the environment in front of the user and modifies the user's motion as necessary to prevent a user from falling down, while the robot performs the ordinary power-assist simultaneously. In addition, the proposed method performs the perception-assist taking into account ZMP to keep stable walking. The experimental results which were carried out by the healthy young man showed the effectiveness of the proposed method.

## ACKNOWLEDGMENT

The authors would like to thank Saga Arizono Prosthetic-Orthotic Company for their cooperation to make the lower-limb power-assist robot used in this study.

## REFERENCES

- [1] A.B. Zoss, H. Kazerooni, and A. Chu, "Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)," *IEEE/ASME Transactions on Mechatronics*, 11(2), 2006, pp. 128-138.
- [2] S. Lee and Y. Sankai, "Power Assist Control for Walking Aid with HAL-3 Based on EMG and Impedance Adjustment around Knee Joint," *Proc. of IEEE/RSJ International Conf. on Intelligent Robots and Systems*, 2002, pp.1499-1504.
- [3] K. Nagai and I. Nakanishi, "Force Analysis of Exoskeletal Robotic Orthoses for Judgment on Mechanical Safety and Possibility of Assistance", *Journal of Robotics and Mechatronics*, 16(5), 2004, pp.473-481.

- [4] L. Lucas, M. DiCicco, and Y. Matsuoka, "An EMG-Controlled Hand Exoskeleton for Natural Pinching", *Journal of Robotics and Mechatronics*, 16(5), 2004, pp.482-488.
- [5] J. Rosen, M. Brand, M. Fuchs, and M. Arcan, "A Myosignal-Based Powered Exoskeleton System", *IEEE Trans. on System Man and Cybernetics, Part A*, 31(3), 2001, pp. 210 - 222.
- [6] N.G. Tsagarkis and D.G. Caldwell, "Development and Control of a 'Soft-Actuated' Exoskeleton for Use in Physiotherapy and Training", *Autonomous Robots*, 15(3), 2003, pp.21-33.
- [7] K. Kiguchi and Q. Quan, "Muscle-Model-Oriented EMG-Based Control of an Upper-Limb Power-Assist Exoskeleton with a Neuro-Fuzzy Adjuster", *Proc. of IEEE World Congress of Computational Intelligence*, 2008, pp.1179-1184.
- [8] R.A.R.C. Gopura and K. Kiguchi, "SUEFUL-7: A 7DOF Upper-Limb Exoskeleton Robot with Muscle-Model-Oriented EMG-Based Control", *Proc. of IEEE/RSJ International Conf. on Intelligent Robots and Systems*, 2009, pp.1126-1131.
- [9] A.B. Zoss, H. Kazerooni, "Biomechanical Design of the Berkley Lower Extremity Exoskeleton (BLEEX)", in *Proc. of the 2006 IEEE/ASME Transactions on Mechatronics*, Vol. 11, No. 2, 2006, pp. 128-138.
- [10] C. Fleischer and G. Hommel, "Embedded Control System for a Powered Leg Exoskeleton", *Embedded Systems - Modeling, Technology, and Applications*, 2006, pp. 177-185.
- [11] A.M. Dollar and H. Herr, "Design of a quasi-passive knee exoskeleton to assist running", *Proc. of IEEE/RSJ International Conf. on Intelligent Robots and Systems*, 2008, pp.747-754.
- [12] H.K. Kwa, J.H. Noorden, M. Missel, T. Craig, J.E. Pratt, P.D. Neuhaus, "Development of the IHMC Mobility Assist Exoskeleton", *Proc. of IEEE International Conf. on Robotics and Automation*, 2009, pp.2556-2562.
- [13] S. Lee, Y. Sankai, "The natural frequency-based power assist control for lower body with HAL-3", *Proc. of International Conference on Systems, Man and Cybernetics*, 2003, pp.1642-1647.
- [14] K. Suzuki, G. Mito, H. Kawamoto, Y. Hasegawa, Y. Sankai, "Intention-Based Walking Support for Paraplegia Patient with Robot Suit HAL", *Climbing and Walking Robots*, 2010, pp.383-408.
- [15] K. Kong and D. Jeon, "Fuzzy Control of a New Tendon-Driven Exoskeletal Power Assistive Device, Proc. of IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 2005, pp.146-151.
- [16] K. Kiguchi and M. Liyanage, "A Study on a 4DOF Upper-Limb Power-Assist Exoskeleton with Perception-Assist", *Proc. of International Conf. on Biomedical Electronics and Devices*, 1, 2008, pp.164-169.
- [17] K. Kiguchi and M. Liyanage, "A Study of a 4DOF Upper-Limb Power Assist Intelligent Exoskeleton with Visual Information for Perception-Assist", *Proc. of IEEE International Conf. on Robotics and Automation*, 2008, pp.3666-3671.
- [18] K. Kiguchi, M. Liyanage and Y. Kose, "Perception Assist with Active Camera for an Upper-Limb Power-Assist Exoskeleton", *Proc. of 3rd Asia International Symposium on Mechatronics*, 2008, pp.387-392.
- [19] K. Kiguchi, M. Liyanage and Y. Kose, "Intelligent Perception Assist With Optimum Force Vector Modification For An Upper-Limb Power-Assist Exoskeleton", *Proc. of IEEE International Conf. on Biomedical Robotics and Biomechatronics*, 2008, pp.175-180.
- [20] K. Kiguchi, M. Liyanage, Y. Kose, Y. Hayashi, and D. Jeon, "3D Perception-Assist for an Upper-Limb Power-Assist Exoskeleton", *Proc. of the 14th IASTED International Conf. on Robotics and Applications*, 2009, pp.60-66.
- [21] A. Tsukahara, R. Kawanishi, Y. Hasegawa, Y. Sankai, "Sit-to-Stand and Stand-to-Sit Transfer Support for Complete Paraplegic Patients with Robot Suit HAL", *Advanced Robotics* Vol.24, No.11, 2010, pp.1615-1638.
- [22] K. Ishii Kihachi, T. Nishiyama, *Textbook series for physical education, Sports and Health Sciences*, Ichimura Publishing House Co., 2002. (in Japanese)
- [23] W. Nakano, Y. Ohashi, "The Influence of Age and Walking Speed on the Adjustment of Step Length for Stepping Over Obstacles," *Physical Therapy Japan*, Vol. 37, No. 3, 2002, pp. 153-159. (in Japanese)