Walking-Assist Principle Analysis for a Multi-Legged System

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As the aging problem becomes increasingly significant, robots are being widely applied as walking-assist devices for elders or patients suffering from walking disabilities. In this paper, a novel walking-assist multi-legged device that is fixed on the waist, with two machine legs independent from human legs, helps elders walk and climb stairs without any manipulation of the machine. In the proposed device, an inertial measurement unit (IMU) sensor is employed; the IMU contains a triaxial accelerometer, a triaxial gyro (angular rate sensor), and a triaxial magnetometer. The sensor is fixed on the waist of the elder in order to gauge the posture of the waist thereby preventing an emergency such as a fall. Further, based on the zero-moment point (ZMP), the stability of the device is analyzed to confirm the feasibility and effectiveness of this device.

Keywords: Walking-assist, Multi-legged, IMU sensor, Fall motion

1. Introduction

Nowadays, lacking in adequate care for the elders, especially those who are walking with inconvenience is becoming a growing problem for the aging society. It is very dangerous that the elders walking with inconvenience when they fall down. It is also necessary for the elders to exercise walking in order to keep normal social life. While walking, elders with little strength usually use canes to keep balance. Consequently, they can not balance their own bodies with one leg, making them walk in a very slow pace while having to step forward quite fast in order to keep balance. For the elders with enough strength in their upper bodies, the canes do work. However, for those without enough strength, keeping balance is nearly impossible merely by canes. Therefore, kinds of walking-assisting carts are proposed. Especially in the rapidly aging Japanese society, elders with walking-assisting carts are quite common.

In order to solve elders’ problem of lacking in strength, many researchers have invented sorts of machine clothes for elders to put on. H. Herr of MIT Media Lab classified exoskeletons and orthoses into devices that act in series and in parallel to a human limb, providing a few examples within each category(8). In Japan, the most representative ones are Honda walking assist devices of Honda Motor Co., Ltd. and Hybrid Assistive Limb (HAL) robot suits. Honda walking assist device with bodyweight support system (2) reduced the floor reaction force of the user was based on biomedical engineering analysis results. Honda prototype stride management assist device (3) was designed to help lift each leg at the thigh as it moves forward and backward. It helps lengthen the user’s stride, covering longer distances at a greater speed.

Y. Sankai et al. proposed an estimation algorithm that infers the intention related to the forward leg-swing in order to support the gait by HAL (4) robot suits. The previously mentioned machines were able to enhance human walking ability, but they paid little attention to keep elders from falling down motion. D. Matsuura et al. proposed a motion control algorithm of walking assist machine using crutches (5). M. Higuchi et al. developed a walking assist machine using crutches (6). But both of them paid little attention to prevent elders from falling down as well.

In this paper, a multi-legged walking assist device which can keep the elders from falling down and help them walk is proposed as Fig. 1. It can also help the elders who have poor walking ability walk by themselves and give them simple walking exercise. In order to measure the human body posture, an IMU sensor fixed on the waist part of human is applied in this research. The IMU sensor can not only measure posture but also measure human walking motion. O.H. Madgwick et al. (7) presented a novel orientation algorithm by a wearable inertial human motion tracking system. The results indicated the algorithm achieving levels of accuracy matching. Y. Hirata et al. (8) focused on the support
of walking on slope, and estimated slope angle based on accelerometer and force sensors. The method was able to apply to Wearable Walking Helper but it was a little complicated. Since the IMU sensor contains a triaxial accelerometer, a triaxial gyro and a triaxial magnetometer. Only one IMU sensor can offer Euler angles to obtain posture angles. Based on this IMU sensor and a mobile manipulator, the authors have already proposed a novel walking assist device\(^{16}\) to help elders walk. It is possible to apply two IMU sensors to tracking elders walk. It is possible to apply two IMU sensors to tracking.

2. Multi-Legged Walking-Assist System

The authors summarize the primary contributions of the paper as follows: 1) the kinematics modeling and dynamics modeling are introduced for this novel multi-legged system; 2) keeping the elders from falling down and help the them walk is proposed; 3) ZMP is introduced as a stability index for the multi-legged system.

2.1 Kinematics Modeling

In this subsection, kinematics of the device leg is described. The joint space position of the device leg in work space is represented as 2-dimensional vector \( x_r = [x_r, y_r]^T \). The end position of the device leg in work space is represented as 2-dimensional vector \( x_h = [x_h, y_h]^T \). Since the device leg base is not fixed but moved by human waist, the 2-dimensional vector \( x_h = [x_h, y_h]^T \) represents the human waist position that measured by the IMU sensor. Forward and inverse kinematics can be derived as follows.

\[
\begin{align*}
\dot{x}_r &= J\dot{q}_r + \dot{x}_b \\
\dot{q}_r &= J^{-1}(\dot{x}_r - \dot{x}_b)
\end{align*}
\]

where \( J \) denotes the Jacobian matrix of the device leg. The Jacobian matrix is used to perform mapping from work space to joint space, and it can be written as the following equation.

\[
J = \begin{bmatrix}
J_{11} & J_{12} \\
J_{21} & J_{22}
\end{bmatrix}
\]

\[
\begin{align*}
J_{11} &= L_1 \cos q_1 + L_2 \cos(q_1 + q_2) \\
J_{12} &= L_2 \cos(q_1 + q_2) \\
J_{21} &= -L_1 \sin q_1 - L_2 \sin(q_1 + q_2) \\
J_{22} &= -L_2 \sin(q_1 + q_2)
\end{align*}
\]

where \( L_1, L_2 \) represent the length of each device leg link.

2.2 Dynamics Modeling

By using the IMU sensor, the 3-D accelerometer, velocity and position of human waist can be measured. Therefore the kinetic energy of human is given by,

\[
K_h = \frac{1}{2}m_h(\dot{x}_h^2 + \dot{y}_h^2)
\]

Kinetic energy of link 1 can be calculated as,

\[
K_1 = \frac{1}{2}m_1[(\dot{x}_1 + l_1 \dot{q}_1 \cos q_1)^2 + (\dot{y}_1 + l_1 \dot{q}_1 \sin q_1)^2] + \frac{1}{2}I_1 \dot{q}_1^2
\]

Potential energy of link 1 can be calculated as,

\[
P_1 = m_1g(y_1 - l_1 \cos q_1)
\]

And the potential energy of link 2 can be calculated as,

\[
P_2 = m_2g(y_2 - L_1 \cos q_1 - l_2 \cos q_2)
\]

Thus the Lagrangian of the device leg is given by,

\[
L = K_h + K_1 + K_2 - P_h - P_1 - P_2
\]

Applying the Lagrangian-Euler formulation for the torque \( \tau = [\tau_1, \tau_2]^T \) at joint 1 and 2 is,

\[
\tau = \frac{d}{dt} \frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q}
\]

where \( q = [x_h, y_h, q_1, q_2]^T \). Dynamics equation of the device is derived from the Euler-Lagrange formulation. It can be
expressed in the joint space as equation (12).

\[ \tau = M(q) \ddot{q} + C(q, \dot{q}) q + G(q) \]  

(12)

where \( M(q) \) is the inertia matrix, \( C(q, \dot{q}) \) represents the Coriolis and centrifugal force, and \( G(q) \) represents the gravity terms.

\[ M(q) = \begin{bmatrix} d_1 \cos q_1 & d_1 \sin q_1 & d_2 & d_3 \cos q_1 \\ d_4 \cos q_2 & d_4 \sin q_2 & d_5 \cos q_2 & d_6 \end{bmatrix} \]  

(13)

\[ C(q, \dot{q}) = \begin{bmatrix} 0 & 0 & 0 & -d_2 dq_2 \sin q_2 \\ 0 & 0 & 0 & 0 \end{bmatrix} \]  

(14)

\[ G(q) = \begin{bmatrix} d_4 g \sin q_1 \\ d_6 g \sin q_2 \end{bmatrix} \]  

(15)

where,

\[ d_1 = m_1 l_1 + m_2 L_1 \\
 d_2 = m_1 l_1^2 + m_2 L_1^2 + I_1 \\
 d_3 = m_2 L_1 l_1 \\
 d_4 = m_2 l_2 \\
 d_5 = m_2 L_1 l_2 \\
 d_6 = m_2 l_2^2 + I_2 \]

2.3 Normal Walking Behavior

Figure 3 shows how the proposed device cooperates with human walking. In order to measure the human gait motion, two tiny encoder links are fixed on the each leg of human. They only measure the rotate angles between posterior and thigh. If human raise his left leg firstly, the right leg of the device will be raised. Similarly, if human raise his right leg firstly, the left leg of device will be raised. Both of the second links of device leg are maintaining an initial angle. Because the impedance control is employed in all of the device links, the joints are flexible.

2.4 Avoid Falling Down Motion

The IMU sensor fixed on the waist can also generate 3-D posture information. A quaternion \((a, b, c, d)\) is a four-dimensional complex number that can be used to represent the orientation of a rigid body or coordinate frame in three dimensional space. Figure 4 shows an arbitrary orientation of frame \(w\) relative to frame \(h\). \(q_h^w\) describes the arbitrary orientation and \(r\) is a unit vector described in frame \(w\).

\[ q_h^w = [a \ b \ c \ d] \]

\[ = \begin{bmatrix} \cos \frac{\sigma}{2} - r_x \sin \frac{\sigma}{2} - r_y \sin \frac{\sigma}{2} - r_z \sin \frac{\sigma}{2} \\ r_x \sin \frac{\sigma}{2} \sin \frac{\sigma}{2} - r_y \sin \frac{\sigma}{2} - r_z \sin \frac{\sigma}{2} \\
 r_y \sin \frac{\sigma}{2} \sin \frac{\sigma}{2} - r_x \sin \frac{\sigma}{2} - r_z \sin \frac{\sigma}{2} \\
 r_y \sin \frac{\sigma}{2} \sin \frac{\sigma}{2} - r_x \sin \frac{\sigma}{2} - r_z \sin \frac{\sigma}{2} \end{bmatrix} \]  

(16)

where \(r_x, r_y, \) and \(r_z\) define the components of the unit vector \(r\) in the \(x, y, \) and \(z\) axes of frame \(w\) respectively.

Applying the quaternion, the Euler angle representation roll \(\theta\) and pitch \(\varphi\) can be defined by,

\[ \theta = -\sin^{-1}(2bd + 2ac) \]  

(17)

\[ \varphi = \tan 2(2cd - 2ab, 2a^2 + 2d^2 - 1) \]  

(18)

To avoid the singular point of the pitch angle, the angles are limited by,

\[-90^\circ \leq \theta \leq 90^\circ \]  

(19)

\[-180^\circ < \varphi < 180^\circ \]  

(20)

In normal walking motion, pitch and roll are almost zero. But in emergency conditions, pitch and roll are not zero absolutely. By applying the vectors of pitch and roll angles, the angle of summation is,

\[ \theta_{1,3} = \angle(\theta + \varphi) \]  

(21)

where \(\theta_{1,3}\) indicates the emergency command angle of link 1 or link 3 in Fig. 5. Emergency situations are defined as a limitation of \(\theta_{1,3}^e\). When \(\theta_{1,3}^e\) bigger than the limitation, this avoiding falling down motion starts working. Otherwise, the multi-legged system works in the normal walking assist motion. Figure 5 explains the falling down motion in the world coordinate as well.

2.5 ZMP Trajectory

The ZMP stability criterion that means it is necessary to keep the ZMP within the support polygon. In this paper, in order to prevent the human from falling down, the ZMP stability of the device needs to be analyzed. Since the diameter of the proposed device legs are small, the ground support polygon is assumed as a point. The IMU sensor that fixed on the human waist part can measure the triaxial acceleration. The position of the IMU sensor can also be assumed as the center of gravity (CoG) of the whole
Controller Design

3.1 Command Generation During the normal walking motion, the two encoder links fixed on human legs supply the rotate commands to the device.

\[
q^{cmd} = \begin{bmatrix} q_{1x}^{cmd} \\ q_{2x}^{cmd} \end{bmatrix} = \begin{bmatrix} 0 \\ q_{2x}^{cmd} \end{bmatrix} \tag{24}
\]

where \(q_{1x}^{cmd}\) and \(q_{2x}^{cmd}\) are encoder link 1 command and encoder link 2 command respectively. But if the pitch or roll angle is bigger than a certain value which means the emergency occurring, the commands are only supplied by IMU sensor. Also, in order to ensure a successful action to stop the falling down motion, the upper limit of rotation angle should be set as well. The command of emergency can be derived as,

\[
q_{e}^{cmd} = q_{e}^{cmd} = H(\tilde{\theta}, \tilde{\phi}) = \begin{bmatrix} K_1 \varepsilon(\tilde{\theta} + \phi) - q_{1b}^{cmd} \\ 0 \\ K_1 \varepsilon(\tilde{\theta} + \phi) - q_{2b}^{cmd} \end{bmatrix} \tag{25}
\]

where \(q_{1b}^{cmd}\) and \(q_{2b}^{cmd}\) are initial angle of the device right leg and left leg before the emergency occurring respectively. The details are showed in Fig. 7.

3.2 Impedance Controller When the device legs touch the ground, the reacting force and the force pushing by human are needed to be considered in Fig. 6. During the device leg touching the ground, assuming the end of device leg dose not slid. The acceleration of human waist is measured by the IMU sensor, then the extend force for each link motor is,

\[
\tau_h = J^T m_h \ddot{x}_h \tag{26}
\]

where \(m_h\) is the mass of testing object. The total extend force for each link motor is,

\[
\tau_{ext} = K_h \tau_h + K_r \dot{x}_m \tag{27}
\]

where \(K_h\) and \(K_r\) are the gains of human force and ground reaction force respectively. \(\dot{x}_m\) is the estimated force of RTOB. By applying the impedance control, the human force acceleration reference is given by,

\[
\ddot{x}_{ref} = \frac{1}{M_i} (\dot{x}_{ext} - D_i \ddot{x}_{ref} - K_i x_{ref}) \tag{28}
\]

To make a big enough force and hold on the human when they falling down, impedance control gains \(M_i, D_i, K_i\) are studied. The transfer function of impedance control is,

\[
\ddot{x}_{ref} = \frac{1}{M_i s^2 + D_i s + K_i} \tag{29}
\]

The natural frequency \(\omega_i\) and damping ratio \(\zeta_i\) are derived as follows.

\[
\begin{align*}
\omega_i & = \sqrt{\frac{K_i}{M_i}} \tag{30} \\
\zeta_i & = \frac{D_i}{2 \sqrt{M_i K_i}} \tag{31}
\end{align*}
\]

To adjust a suitable value for the natural frequency and damping ratio, the impedance control gains \(D_i, K_i\) are be determined as follows.

\[
\begin{align*}
D_i & = 2 \zeta_i \omega_i M_i \tag{32} \\
K_i & = \omega_i^2 M_i \tag{33}
\end{align*}
\]

By applying the RTOB and IMU sensor to get the enviroment force, the device motor rotate acceleration reference is given by,
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Fig. 6. Block diagram of proposed controller

\[ q_{ref} = -q_{ref}^{hum} + K_1(q_{cmd}^{hum} - q_{ref}^{hum}) + K_2(q_{cmd}^{hum} - q_{ref}^{hum}) \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad (34) \]

Figure 7 shows the command generation. For the normal walking cases, the system command \( q_{cmd}^{cmd} = q_{cmd}^{cmd} \). For the emergency cases, the system command \( q_{cmd}^{cmd} = q_{cmd}^{cmd} \). The testing subject of this experiment was a 28 years old man. His height was 175cm and weight was about 60 kg. An iBIS system that is a PC based DSP was used as a processor in this device. A 24 V battery was used to supply power for the whole system. The total mass of this device was about 15 kg. The parameters of device and controller are shown in Table 1 and Table 2.

4. Experiments

In this section, experiment procedures and results are explained. In these experiments, normal walking motion and falling down motion were conducted with the proposed controller. Figure 8 shows the real device in the world coordinate. The testing subject of this experiment was a 28 years old man. His height was 175cm and weight was about 60 kg. An iBIS system that is a PC based DSP was used as a processor in this device. A 24 V battery was used to supply power for the whole system. The total mass of this device was about 15 kg. The parameters of device and controller are shown in Table 1 and Table 2.

4.1 Experiment Procedures

4.1.1 Experiment 1 Normal Walking Motion

The device legs can touch the ground like the human using two crutches while walking. Therefore, adding the human two legs, there are four legs in total. Four legs walking can make elders feel there is something to rely. This experiment goal is to know whether the device enables to coordinate with human walking motion.

4.1.2 Experiment 2 Falling Down Motion

Makes the device inclined at a small angle for a test firstly. This test guarantees the system command following the encoder links but not the IMU sensor. Then tests are done for the subject falling forward which means the emergency occurs. After the device legs stop the falling down motion, the testing subject returned to a normal posture by himself. This experiment’s goal is to enable the two machine legs to prevent elders from

Table 1. Physical parameters of device

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Width of the machine W</td>
<td>0.420</td>
</tr>
<tr>
<td>Length of links (the first link of each leg) ( l_1, l_3 ) [m]</td>
<td>0.435</td>
</tr>
<tr>
<td>Length of links (the second link of each leg) ( l_2, l_4 ) [m]</td>
<td>0.543</td>
</tr>
<tr>
<td>CoG length of links ( l_1, l_3 ) [m]</td>
<td>0.210</td>
</tr>
<tr>
<td>CoG length of links ( l_2, l_4 ) [m]</td>
<td>0.270</td>
</tr>
<tr>
<td>Length of encoder links [m]</td>
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</tr>
<tr>
<td>Mass of link 1 and 3 ( m_1, m_3 ) [kg]</td>
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</tr>
<tr>
<td>Mass of link 2 and 4 ( m_2, m_4 ) [kg]</td>
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</tr>
<tr>
<td>Mass of testing object ( m_h ) [kg]</td>
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</tr>
<tr>
<td>Rotary encoder resolution ( R_e ) [PPR]</td>
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</tr>
<tr>
<td>Gear reduction of motors ( G_r )</td>
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Table 2. Parameters of controller

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>Position gain ( K_1 )</td>
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<tr>
<td>Velocity gain ( K_1 )</td>
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<tr>
<td>Human force gain ( K_2 )</td>
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<tr>
<td>Ground reaction force gain ( K_3 )</td>
<td>0.7</td>
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<tr>
<td>Virtual mass gain ( M_r )</td>
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<tr>
<td>Virtual viscosity gain ( D_r )</td>
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<tr>
<td>Virtual spring gain ( K_r )</td>
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<tr>
<td>Cut off frequency of DOB</td>
<td>50.0</td>
</tr>
<tr>
<td>Cut off frequency of RTOB</td>
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<tr>
<td>Sampling time ( dt ) [ms]</td>
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</tr>
</tbody>
</table>
4.2 Experiment Results

4.2.1 Experiment 1 Results  
Figure 9 shows the results of experiment 1. There are four normal walking steps in the experiment. In Fig. 9 (a), the machine leg link 1 motor tracks the encoder link 1 command. The tracking error depends on the gains $K_1, K_2$. If the position gain is larger, the tracking error is smaller. But it does not mean that the smaller the error is, a better system response is achieved. In order to reduce the sensitivity of the system, the gains should not be very large. Since the velocity command is noisy, the velocity gain should be reduced accordingly as well. In this paper, for link 1 and link 3, the position and velocity gains were chosen as 400 and 40 respectively. The bound of position gain is recommended between 100 to 625. In accordingly, the bound of velocity gain is recommended between 20 to 50. For link 2 and link 4, the position and velocity gains were chosen as 100 and 20 respectively. The bound of position gain is recommended between 81 to 225, and the bound of velocity gain is recommended between 18 to 30. The tracking command of the machine leg link 2 is zero. But because of impedance control, the rotation result is not always zero. The RTOB results indicate that there is an obvious reaction force when the machine leg has contacted with the ground.

To analyse the stability of the device with human walking, ZMP tracking performance is introduced in Fig. 10. Measuring $CoG_x$ and measuring $CoG_z$ are obtained by the IMU sensor. $ZMP_x$ and $ZMP_z$ are obtained by equations (22) and (23) respectively. Because this device is not similar to the biped robot, there is no desired ZMP trajectory in advance. In this paper, reference $ZMP_x$ is a point connection from the experiment data. It is only a reference for the system stability. The flex points are decided by the moments of device contacting or leaving the ground. Denotes the rotate position is 0 m in 0 second as (0, 0), the other flex points are (0.58, 0, 1.33), (0.4, 2.77), (0.4, 3.55), (0.74, 4.67), (0.74, 5.72), (1.1, 6.84), (1.1, 7.47) and (1.35, 8.40). $T_r$ and $T_l$ are the period of single support phase of right and left device leg respectively. $T_d$ is double support phase period, $S$ is the device stride of one step. Reference $ZMP_z$ is obtained by the similar way as $ZMP_x$. $-0.21$ m or $0.21$ m is a half of the device width $W$. $-0.1$ m or $0.1$ m is a half of the distance between the two feet of human. The results show the whole system is very stable during the human walking in a normal slow speed motion.

4.2.2 Experiment 2 Results  
There are many kinds of falling down motion for the elders. For simplicity, only falling forward motion was considered. Also, the device two legs did the same motion in this emergency case. Figure 11 and Fig. 12 show the results of experiment 2. In the experiment, the current device motors did not have enough power to hold on the human body when he falls down. In the future work, we need to change bigger motors for the device links. Therefore in this experiment, for the safety, the testing subject fell forward and used his hands to support on a wall. That is why the RTOB force is not very big in Fig. 11.

In Fig. 12(a), reference $ZMP_z$ is obtained in the same way as the normal walking motion. Because human feet did not move on the ground in this experiment, there is no reference $ZMP_z$ data for the human. $T_l$ and $T_r$ are the period of falling down motion.
down and recovery respectively. $T_f$ is device holding period. Maybe this case can not represent all of falling down motions, but at least it can make it possible to prevent elders from falling down. In Fig. 12(b), machine reference $ZMP_{m}$ and human reference $ZMP_{h}$ are obtained by the similar way as reference $ZMP_{ref}$. The time of flex points are 0 s, 2.95 s, 3.94 s, 5.6 s, 6.79 s and 8.3 s. During the period of $T_f$ and $T_r$, because both of the device two legs are leaving the ground, there is no data for the machine reference $ZMP_{ref}$. The results show the whole system is stable even in this falling forward down motion. Finally, if this system is applied to various users, the initial joint angle device of two legs should be adjusted according to the height of the user. Also, the impedance control gains are need to be adjusted according to different weight users.

5. Conclusion and Future Works

In this paper, a novel multi-legged system device is proposed. The purpose of this research is to hold and help elders walk using two robotic crutches and prevent them from falling down when an emergency occurs. Since the device legs are 2 DOF manipulators, only forward falling down motions were discussed. ZMP tracking results was introduced as a stability index for the whole system. The results also indicated that the proposed device can stop human from falling down when the emergency occurs. After this falling forward down motion, human can return to the normal safe posture by themselves and keep on normal walking. As a future work, two 3 DOF manipulators need to be considered. Then it is possible to consider about the other kinds of falling down motions. In addition, variable impedance should be designed to increase the performance, based on different cases.

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References


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