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Control and Evaluation on Powered Assistive Systems for Standing-up Motion

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ABSTRACT

Physically weak or elderly people often require support for standing-up motion. The purpose of this study is to develop a new powered assistive system for standing-up motion. The positions of the vertical / horizontal axes of the assistive system have been controlled by using the internal model control (IMC) with feedback controller. The several target trajectories for standing-up motion have been considered in order to support users. Effectiveness of the assistive system has been evaluated by comparative experiments. Muscle activities have been also observed by using surface electromyography (EMG) for evaluating the proposed assistive system.

Index Terms **–** Assistive devices for standing-up motion, Internal model control, Disturbance estimation

1. INTRODUCTION

Standing-up motion is one of important actions in daily life. Physically weak or elderly people often require the assistive systems for standing-up motion. The commercial products for standing-up only push up the bottom or pull up the body of users. An appropriate support trajectory by using such kind of assistive devices has not been researched well. Furthermore, observation studies of muscle activity by using assistive devices are little.

We propose an appropriate target trajectory and a control method of assistive devices for standing-up motion in this paper. We develop a powered assistive system with few restraints. The internal model control (IMC) based controller is implemented for controlling the assistive system. The IMC-based controller has good disturbance estimation property. We can estimate dependency of users on the assistive devices.

The several target trajectories for standing-up is considered in order to support users. Effectiveness of the assistive system is evaluated by comparative experiments. Muscle activities are also observed by using surface electromyography (EMG) for evaluating the proposed assistive system.

2. EXPERIMENTAL DEVICE AND SYSTEM CONFIGURATION

Fig. 1 shows the proposed powered assistive system, and Fig. 2 shows the system configuration. The positions of the vertical / horizontal axes of the support part of the upper body are controlled by using the IMC-based controller. The support part of arms synchronously moves with the support part of the upper body.

The mechanism of the support part is independent of vertical movement and horizontal movement. Each mechanism consists of a DC-motor, a belt pulley, and an actuator named Zip-chain actuator. Rotary encoders are attached to measure rotational angles of the two DC motors. The IMC-based controller is implemented by the real-time control software MATLAB / Simulink and xPC-Target.

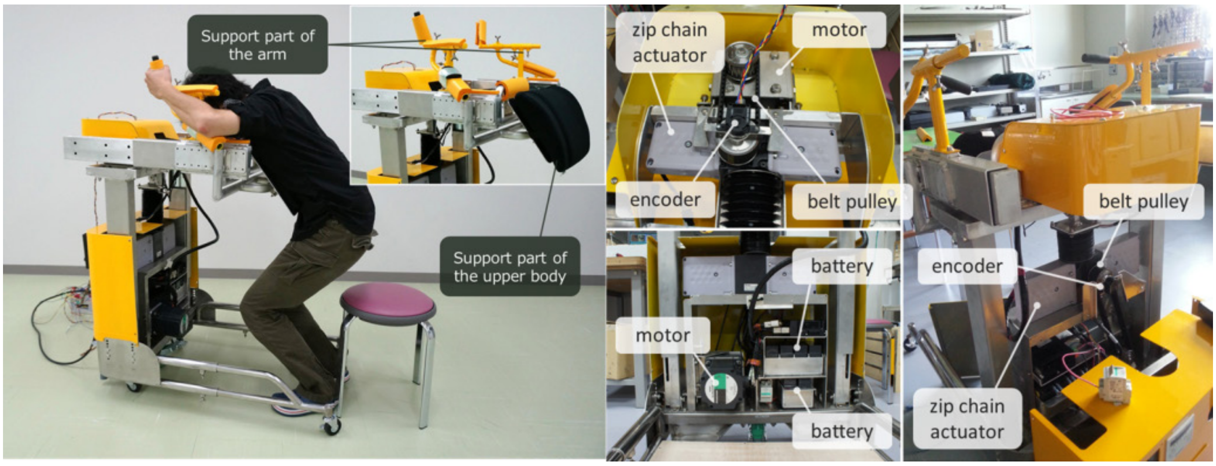


Fig. 1 Assistive system for standing-up

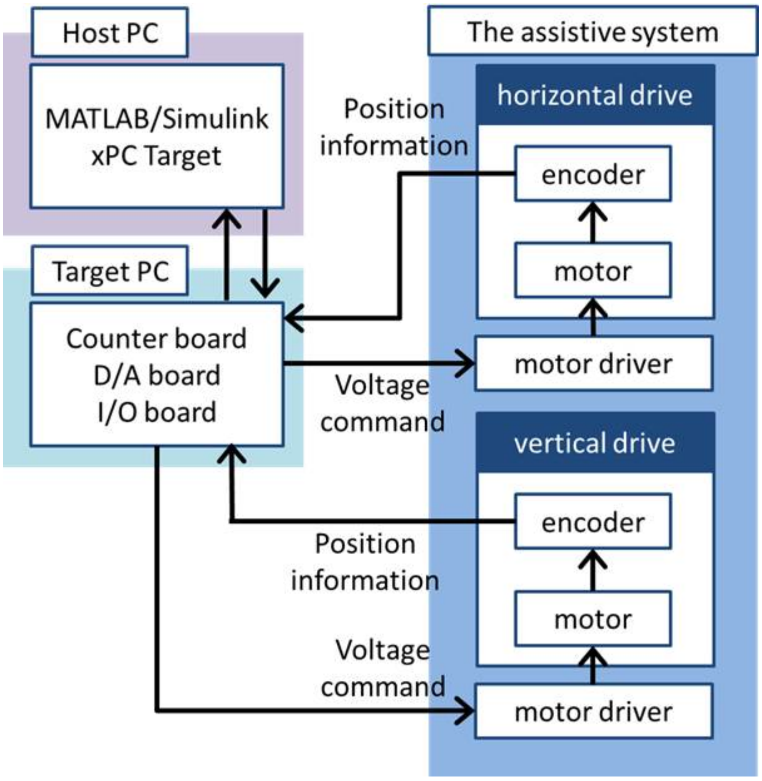


Fig. 2 System configuration

3. CONTROL METHOD FOR ASSISTIVE SYSTEM

Internal model control (IMC) with a feedback shown in Fig. 3 is applied to control the vertical / horizontal axes of the support part of the upper body. Here, Σ_f is the control object (the assistive system) with feedback, $\overline{\Sigma}_f$ is the mathematical model of the control object, $\overline{\Sigma}_{f\rho *}^{-1}$ is an approximate inverse system of $\overline{\Sigma}_f$. r is an input vector, y is an output vector, ξ is disturbance added on the input terminal, $\hat{\xi}$ is the estimate value of ξ. The positions of the support part of the upper body are controlled by using this controller in order to generate an appropriate trajectory.

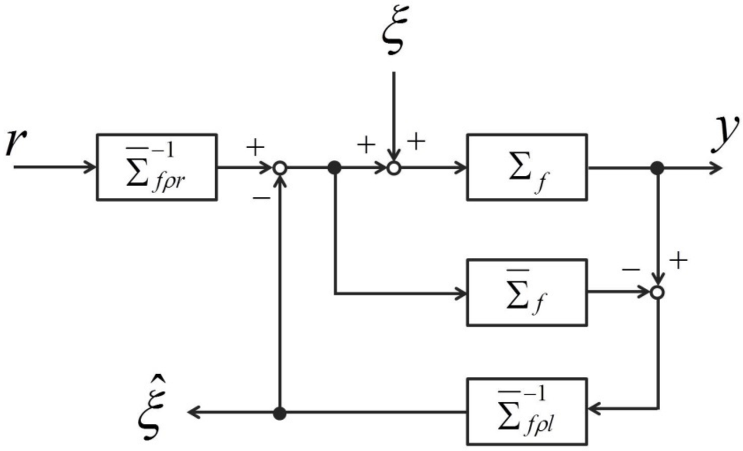


Fig. 3 Internal model control with feedback controller

3.1 Internal model control with feedback controller

Consider the following linear system with disturbance

$$\begin{cases} \dot{x} = Ax + Bu + B\xi \\ y = Cx \end{cases},$$

where $x \in R^n$ is a state vector, $u \in R^m$ is an input vector, $\xi \in R^m$ is unknown disturbance, $y \in R^m$ is an output vector. The closed-loop system is constructed by using the following feedback

$$u = F_\varepsilon x + v.$$

The feedback gain $F_\varepsilon = -B^T P$ for a LQ optimal control is obtained by the following riccati equation as $\varepsilon \to 0$.

$$A^T P + PA - PBB^T P + \frac{1}{\varepsilon^2} C^T C = 0$$

The approximate inverse system $\overline{\Sigma}_{f\rho *}^{-1}$ is defined as

$$\overline{\Sigma}_f \, \overline{\Sigma}_{f\rho r}^{-1} = diag\left((\rho s+1)^{-d_1}, \cdots, (\rho s+1)^{-d_m}\right)$$
$$\overline{\Sigma}_{f\rho l}^{-1} \, \overline{\Sigma}_f = diag\left((\rho s+1)^{-d_1}, \cdots, (\rho s+1)^{-d_m}\right).$$

Here $\rho << 1$ and d_i is the integral index to obtain a proper approximate inverse system.

$$\lim_{\rho \to 0} \overline{\Sigma}_f \, \overline{\Sigma}_{f\rho r}^{-1} = \lim_{\rho \to 0} diag\left((\rho s+1)^{-d_1}, \cdots, (\rho s+1)^{-d_m}\right) = I$$
$$\lim_{\rho \to 0} \overline{\Sigma}_{f\rho l}^{-1} \, \overline{\Sigma}_f = \lim_{\rho \to 0} diag\left((\rho s+1)^{-d_1}, \cdots, (\rho s+1)^{-d_m}\right) = I$$

H_{yr} is the transfer function from the input r to the output y, $H_{y\xi}$ is the transfer function from the unknown disturbance ξ to the output y, and $H_{\hat{\xi}\xi}$ is the transfer function from the unknown disturbance ξ to the estimated disturbance $\hat{\xi}$. If $\Sigma_f = \overline{\Sigma}_f$ and $\rho \to 0$, then each transfer functions become in below.

$$H_{yr} = I$$
$$H_{y\xi} = 0$$
$$H_{\hat{\xi}\xi} = I$$

These statements mean that the IMC with feedback controller shown in Fig. 3 has trajectory tracking property, disturbance rejection property and disturbance estimation property.

The model of the proposed assistive system is shown in Fig. 4. The mathematical model of the system is obtained as follows

$$\begin{cases} m_1\ddot{x}_1 + c_1\dot{x}_1 = u_1 + \xi_1 \\ m_2\ddot{x}_2 + c_2\dot{x}_2 = u_2 + \xi_2 \end{cases}.$$

x [m] is the displacement of the support part of the upper body, c [Ns/m] is the damping coefficient, u is the input vector, ξ is unknown disturbance which is loaded by user. The subscript 1 means horizontal mechanism, the subscript 2 means vertical mechanism. m_1 [kg] is mass of the horizontal mechanism, m_2 [kg] is mass of the support part of the upper body and horizontal mechanism.

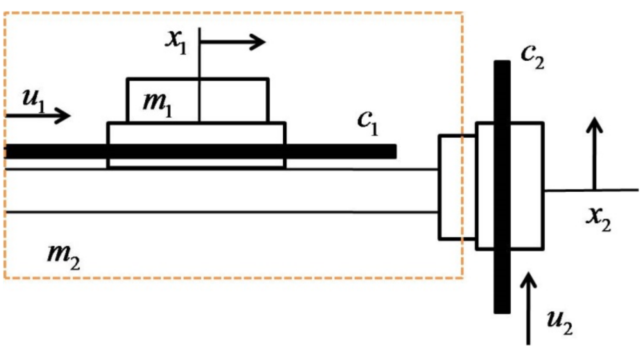


Fig. 4 Model of horizontal / vertical mechanism

The above equation is represented as follows.

$$\Sigma:\begin{cases}\dot{x}=\begin{pmatrix}0 & 1 & 0 & 0\\ 0 & -\dfrac{c_1}{m_1} & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 0 & -\dfrac{c_2}{m_2}\end{pmatrix}x+\begin{pmatrix}0 & 0\\ \dfrac{1}{m_1} & 0\\ 0 & 0\\ 0 & \dfrac{1}{m_2}\end{pmatrix}u+\begin{pmatrix}0 & 0\\ \dfrac{1}{m_1} & 0\\ 0 & 0\\ 0 & \dfrac{1}{m_2}\end{pmatrix}\xi\\ y=\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{pmatrix}x\end{cases}$$

Here, the state value $x=\begin{pmatrix}x_1 & \dot{x}_1 & x_2 & \dot{x}_2\end{pmatrix}^T$ is displacements and velocities of each axis. $u=\begin{pmatrix}u_1 & u_2\end{pmatrix}^T$ is the input vector, $\xi=\begin{pmatrix}\xi_1 & \xi_2\end{pmatrix}^T$ is unknown disturbance. The system compensated with the feedback $u=F_\varepsilon x+v$ is represented as follows

$$\overline{\Sigma}_f:\begin{cases}\dot{x}=\begin{pmatrix}0 & 1 & 0 & 0\\ \dfrac{f_{11}}{m_1} & \dfrac{f_{12}-c_1}{m_1} & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & \dfrac{f_{21}}{m_2} & \dfrac{f_{22}-c_2}{m_2}\end{pmatrix}x+\begin{pmatrix}0 & 0\\ \dfrac{1}{m_1} & 0\\ 0 & 0\\ 0 & \dfrac{1}{m_2}\end{pmatrix}v\\ y=\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{pmatrix}x\end{cases}.$$

Here, the feedback gain F_ε is

$$F_\varepsilon=\begin{pmatrix}f_{11} & f_{12} & 0 & 0\\ 0 & 0 & f_{21} & f_{22}\end{pmatrix}.$$

The approximate inverse system $\overline{\Sigma}_{f\rho^*}^{-1}$ is given by

$$\overline{\Sigma}_{f\rho^*}^{-1}:\begin{cases}\dot{z}=\begin{pmatrix}0 & 1 & 0 & 0\\ -\dfrac{f_{11}}{m_1} & \dfrac{f_{12}-c_1}{m_1} & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & -\dfrac{f_{21}}{m_2} & \dfrac{f_{22}-c_2}{m_2}\end{pmatrix}z+\begin{pmatrix}0 & 0\\ 1 & 0\\ 0 & 0\\ 0 & 1\end{pmatrix}q\\ w=\begin{pmatrix}-\dfrac{m_1}{\rho^4}-\dfrac{f_{11}}{\rho^2} & \dfrac{c_1-f_{12}}{\rho^2}-\dfrac{2m_1}{\rho^3} & 0 & 0\\ 0 & 0 & -\dfrac{m_2}{\rho^4}-\dfrac{f_{21}}{\rho^2} & \dfrac{c_2-f_{22}}{\rho^2}-\dfrac{2m_2}{\rho^3}\end{pmatrix}z+\dfrac{m_2}{\rho^2}q\end{cases}.$$

4. EXPERIMENTAL RESULTS

The validity of the proposed assistive system is confirmed through experiments. The support part of the upper body is controlled by setting the target value. First, target tracking performance is evaluated by experiments. Second, trajectories of standing-up motion with assists and without assist are compared. Next, muscle activities are observed by using a surface electromyography for evaluating effectiveness of the powered assistive system.

4.1 Appropriate trajectory generation for standing-up motion

We observe shoulder trajectories during standing-up in order to generate an appropriate trajectory for supporting standing-up motion. Fig. 5 shows a flow of standing-up motion with the proposed assistive system. Fig. 6 shows shoulder trajectories captured by a video camera during standing-up.

The assistive system supports as follows; (1) users put their arms on the support part of arms and put their breast on the support part of the upper body, (2) the assistive system moves a little downward vertically to make users a stooped posture, (3) the assistive system moves forward and upward direction simultaneously, (4) users can depend on the assistive system during the machine support, or users can release the assistive system any time in adequately positions.

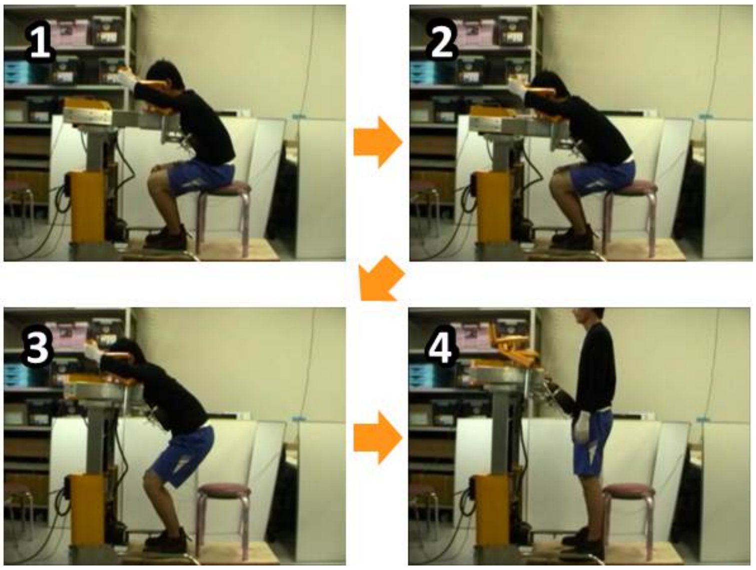


Fig. 5 Standing-up motion with assistive devices

We define the following three assist methods.

(1) Assist 0: (without assist)
Users stand up without powered assistive system.

(2) Assist 1: (assistive system 1)
Users stand up with assistive system 1. The input trajectory is given by a straight line with an obliquely upward direction.

(3) Assist 2: (assistive system 2)
Users stand up with assistive system 2. The input trajectory is given by a curved line. The horizontal axis system moves with a constant velocity. And simultaneously, the vertical axis descends with a constant velocity, shortly after that the vertical axis moves upward with a constant acceleration.

In Fig. 6, the blue solid line shows the shoulder trajectory without the assistive system, the green solid line shows the trajectory with Assist 1, and the red solid line shows the trajectory with Assist 2, respectively. The horizontal axis shows horizontal direction [mm], the vertical axis shows vertical direction [mm]. The shoulder trajectory of an ordinary person is captured as the blue solid line shown in Fig. 6. We control the support part of the upper body to generate an appropriate trajectory for standing-up like the blue curved line in Fig. 6.

Two target trajectories of Assist 1 and Assist 2 are demonstrated to generate the appropriate trajectory. The green line shows the experimental result by using Assist 1 and the red line shows the result by using Assist 2 in Fig. 6. We can see that the support part of the upper body is controlled with the appropriate trajectory. The shoulder trajectory of the user with Assist 2 (the red line) describes well like the trajectory without assistive devices (the blue line).

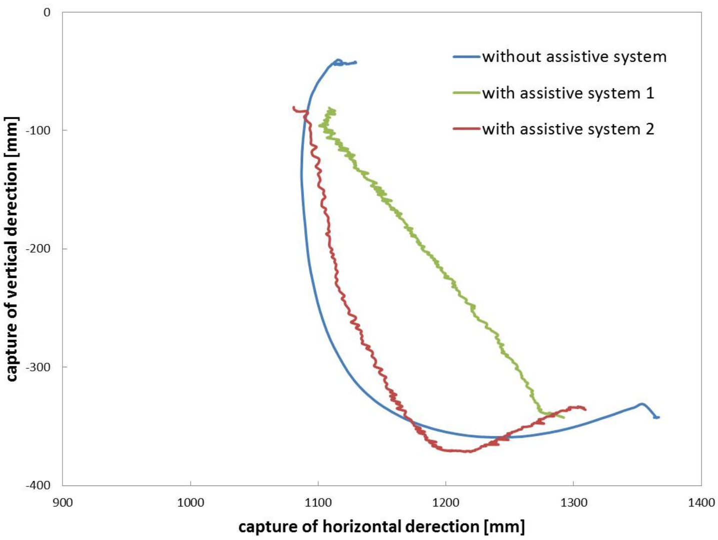


Fig. 6 Shoulder trajectories during standing-up motion (captured by video camera)

4.2 Performance evaluation on position control

We evaluate the IMC based controller implemented the proposed assistive system. The target trajectory (input) for the support part of the upper body is given by a curved line (the blue solid line) shown in Fig. 7. Here, we evaluate control performance. The weights (loads) to the support part are changed from 0 kg to 18 kg. Fig. 7 shows the experimental results on position control. The horizontal axis shows horizontal displacement and the vertical axis shows vertical displacement.

From the results of Fig. 7, the position of the support part follows almost the target trajectory (input) with different size of weights. Therefore, the IMC based controller implemented the assistive system is robust against load changes.

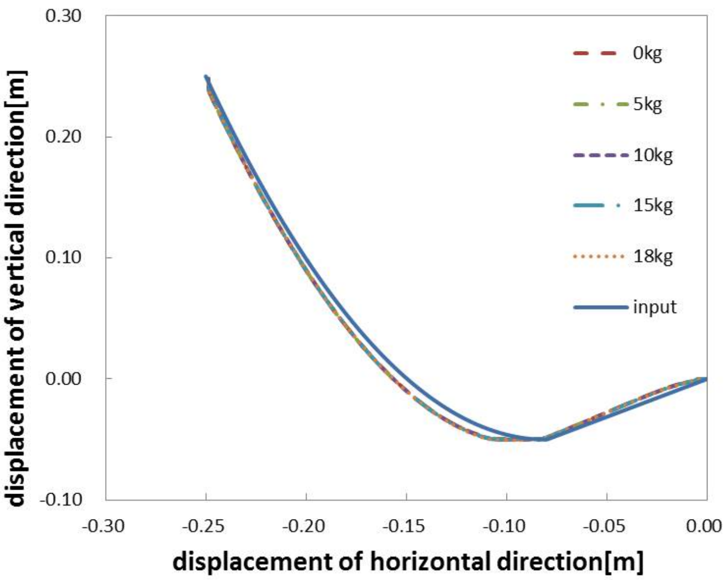


Fig. 7 Trajectory of controlled support part

4.3 Observations of muscle activity value

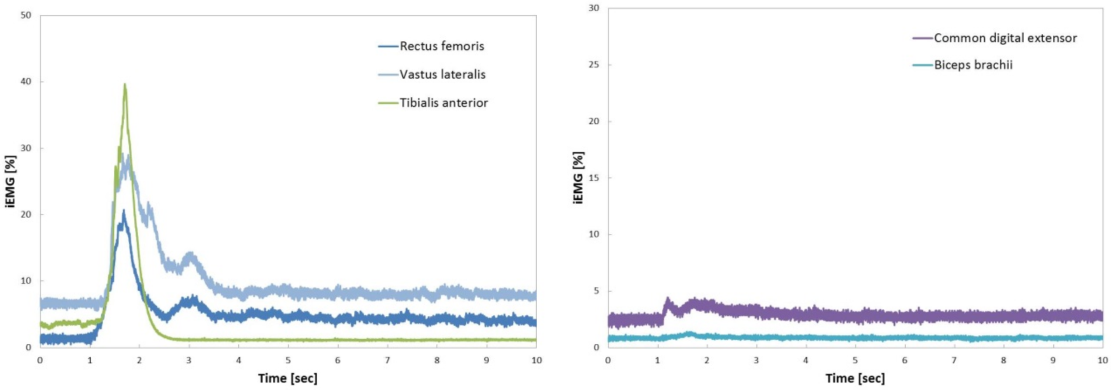
We observe muscle activities on standing-up motion by using surface electromyography (EMG). Measurement points on the lower limb are rectus femoris, vastus lateralis and tibialis anterior. The measurement data are shown in Fig. 8, Fig. 9, and Fig. 10. Fig. 8 shows the muscle activity data without any assist. Fig. 9 shows the data with the assistive system 1 (Assist 1). Fig. 10 shows the data with the assistive system 2 (Assist 2). The horizontal axis shows time [s], the vertical axis shows normalized value [%] by maximum integral electromyogram value. In the each figure of the left hand side, the blue line is rectus femoris, the light blue line is vastus lateralis, and the green line is tibialis anterior. On the right hand side, the purple line is common digital extensor, the sky blue line is biceps brachii.

From Fig. 8 to Fig. 10, maximum values of vastus lateralis are almost same. We can see that maximum values of tibialis anterior are decreased by using both assistive systems compared with Fig. 8. The proposed assistive system is helpful for a person with weak tibialis anterior.

We compare the result of Fig. 9 with Fig. 10. The muscle activity value with the assistive system 2 is a little by comparing the assistive system 1. The muscle activities of common digital extensor and biceps brachii are also slightly decreased. The result means the target trajectory with the curve line shown in Fig. 7 is much better than the straight line for supporting standing-up motion.

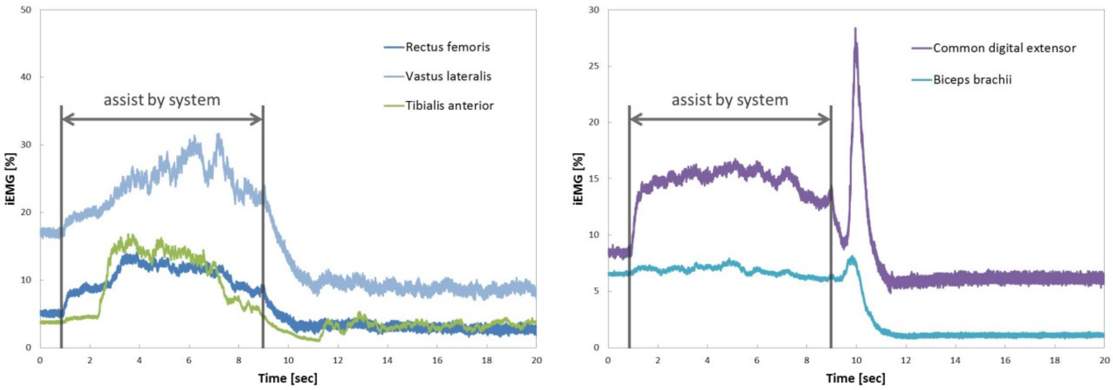
5. CONCLUSION

We developed the powered assistive system for standing-up motion. The control method for the assistive system was proposed in order to generate an appropriate trajectory by using the IMC-based controller. Effectiveness of the control method was evaluated by comparative experiments. Muscle activities with the assistive system were observed by using electromyography (EMG). The users could stand up less muscular power. The proposed system was assisted muscle of tibialis anterior on standing-up motions. The proposed assistive system will be able to support for standing-up motions at home or hospitals as a rehabilitation machine.



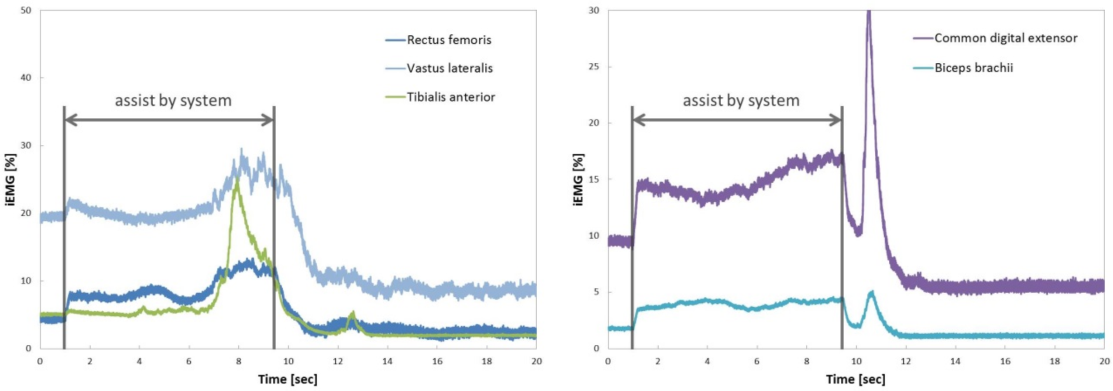
(a) Muscle activity of leg (b) Muscle activity of arm

Fig. 8 Muscle activity value without assistive system



(a) Muscle activity of leg (b) Muscle activity of arm

Fig. 9 Muscle activity value with assistive system 1



(a) Muscle activity of leg (b) Muscle activity of arm

Fig. 10 Muscle activity value with assistive system 2

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REFERENCES

[1] Hui He, Etsuo Horikawa, "A Study on Lower-Limb Muscle activities during Daily Lower-Limb Motion", *International Journal of Bioelectromagnetism*, Vol. 9, No. 2, pp. 79-84, 2007.

[2] Qi An, Y. Ikemoto, H. Asama, H. Matsuoka, D. Chugo, and K. Takakusaki, "Extraction of Behavior Primitives in Human Standing-up Motion for Development of Power Assisting Machine", *Proceedings of the 2008 IEEE International Conference on Robotics and Biomimetics*, pp. 1995-2000, 2009.

[3] Qi An, H. Asama, C. E. Stepp, and Y. Matsuoka, "Uncontrolled Manifold Analysis of Standing-up motion for Development of an Assistance System", *Proceedings of the 2011 IEEE International Conference on Rehabilitation Robotics*, 2011.

[4] R. Suzuki, E. P. Hofer, M. Tani, N. Fujiki, and N. Kobayashi, "Force Detection to an Assistive Device in Rehabilitation Medicine", *Proceedings of the XII International Symposium on Dynamic Problems of Mechanics*, DIN-07-015, 2007.

[5] R. Suzuki, M. Doi, N. Kobayashi, and S. Furuya, "IMC Design with Limiting Properties of LQR and Its Application to Trajectory Tracking Control", *Proceedings of the 1999 IEEE International Conference on Control Applications*, pp. 674-679, 1999.

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