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Paper:

Set-Point Control of a Musculoskeletal System Under Gravity by a Combination of Feed-Forward and Feedback Manners Considering Output Limitation of Muscular Forces

Yuki Matsutani*, **Kenji Tahara****, **and Hitoshi Kino*****

*Department of Robotics, Faculty of Engineering, Kindai University
1 Takaya Umenobe, Higashi-hiroshima, Hiroshima 739-2116, Japan
E-mail: matsutani@hiro.kindai.ac.jp
**Department of Mechanical Engineering, Kyushu University
744 Moto'oka, Nishi-ku, Fukuoka 819-0395, Japan
E-mail: tahara@ieee.org
***Department of Intelligent Mechanical Engineering, Fukuoka Institute of Technology
3-30-1 Wajirohigashi, Higashi-ku, Fukuoka 811-0295, Japan
E-mail: kino@fit.ac.jp

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This paper proposes a new control method for musculoskeletal systems, which combines a feed-forward input with a feedback input, while considering an output limit. Our previous research proposed a set-point control that used a complementary combination of feedback using a time delay and a muscular internal force feed-forward; it achieved robust and rapid positioning with relatively low muscular contraction forces. However, in that control method, the range of motion of the musculoskeletal system was limited within a horizontal plane. In other words, that system did not consider the effect of gravity. The controller proposed in this paper can achieve the reaching movement of the musculoskeletal system without requiring accurate physical parameters under gravity. Moreover, the input of the proposed method can be prevented from becoming saturated with the output limit. This paper describes the design of the proposed controller and demonstrates the effectiveness of the proposed method based on the results of numerical simulations.

Keywords: musculoskeletal system, reaching movement, gravity compensation

1. Introduction

Humans can realize rapid movements within several milliseconds, even though the visual information includes a large time delay of more than 100 ms. These movements, including the large time delay, are difficult to realize by a visual feedback controller. Therefore, a feed-forward controller is important to the brain's control strategy. However, movements that adapt to an unknown environment are difficult to realize with a feed-forward controller. Therefore, the brain's control strategy is an appropriate combination of feed-forward and feedback controllers.

In our previous work, we proposed a control method by combining feed-forward and feedback control for a musculoskeletal system [1, 2]. This control method linearly combines a muscular internal force feed-forward control [3–6] with a sensory feedback control including a time delay [1]. The muscular internal force feed-forward control method can achieve position control without the use of sensors by providing the muscular internal force balancing as an input at a desired position into the muscles. The muscular internal force balancing at the desired position makes a potential field. When the stable equilibrium point of the potential field is formed at the desired position, the motion of the musculoskeletal system converges at the desired position. The advantage of this method is that the control input is calculated using kinematics alone, without needing a dynamical model or repeating the trial. The disadvantage of this method is that the control input needs to be set in excess to achieve high control performance, because the control performance depends on the shape of the potential field. The feedback controller was combined with the muscular internal force feed-forward control method to overcome this disadvantage. Moreover, a variable function is introduced into this control method in order to vary the ratio of each input in response to the end-point position [2]. If the reaching movement of the musculoskeletal system is impeded by external forces, the system can achieve flexible movement according to the external force, and rapid return movement after removing the external force. However, the movement of the musculoskeletal system is limited to the horizontal plane, which is not affected by gravity. It is unknown how the system reacts to the behavior with regard to gravity and time delay.

Thus far, various control methods with gravity com-

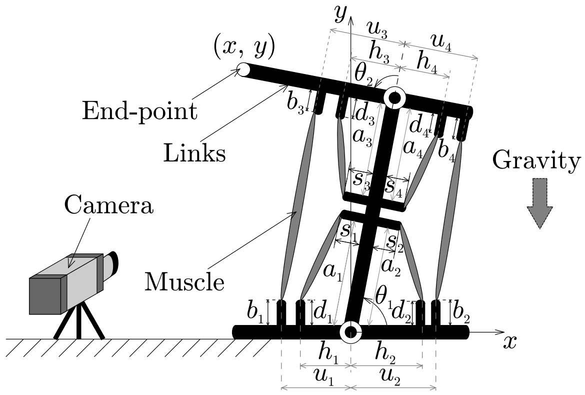

Fig. 1. Musculoskeletal system.

pensation [7–18] and various mechanistic compensating methods [19–21] for reaching movements under the effect of gravity have been reported. For example, Arimoto [7] proposed a control method with adaptive gravity compensation that can achieve accurate movement by estimating unknown physical parameters. Because sensory information is required, this method does not have the information concerning how the system can be moved in the case of using sensory information, including time delay. Moreover, gravity compensation methods have been proposed for flexible-joint robots [8–11], flexible-link robots [12], and musculoskeletal systems [13, 14], in addition to general robots. Tahara et al. [13, 14] proposed an adaptive gravity compensation method for the musculoskeletal system. This method can compensate for gravity by estimating parameters even when the mass of the link is unknown. Because accurate sensory information is required, this method does not know how far the parameters can be estimated in the case of using sensory information, including time delay. Other methods do not consider the time delay of the sensory information [15–18]. In summary, a control method of the musculoskeletal system under gravity without accurate physical parameters or accurate sensory information has not been proposed.

Therefore, this paper proposes a new control method, which can achieve reaching movements of the musculoskeletal system under the effect of gravity. In this proposed method, a gravity compensation term at the desired position is added to the feed-forward input part of the conventional method, and an integral term is added to the feedback input part.

The remainder of this paper is organized as follows. Section 2 describes the kinematics of musculoskeletal systems. The proposed control method is presented in Section 3 and simulation results are presented in Section 4. Section 5 contains our conclusions.

2. Musculoskeletal System

Figure 1 shows the musculoskeletal system considered in this study. This system consists of two joints and six muscles (four mono-articular muscles and two bi-articular muscles). Furthermore, it is assumed that there is no movement of mass because the mass of the muscles is contained in the mass of the links. The movement of system is constrained in the vertical two-dimensional plane under the gravity effect. In addition, offsets are explicitly set between the link and muscular attachments. These are important parameters, which influence the convergence of the muscular internal force feed-forward control method [3–6].

2.1. Relationship Between End-Point and Joint Spaces

The relationship between the end-point position vector $\boldsymbol{x}(t) \in \mathbf{R}^2$ and the joint angle vector $\boldsymbol{\theta}(t) \in \mathbf{R}^2$ for the musculoskeletal system, as shown in **Fig. 1**, is given by the following equation:

$$\boldsymbol{x}(t) = \begin{bmatrix} L_1C_1 + L_2C_{12} \\ L_1S_1 + L_2S_{12} \end{bmatrix}, \quad \ldots\ldots\ldots\ldots \quad (1)$$

where L_n $(n = 1, 2)$ is the link length, S_n and C_n are defined $S_n = \sin\theta_n(t)$ and $C_n = \cos\theta_n(t)$, S_{12} and C_{12} are defined $S_{12} = \sin(\theta_1(t) + \theta_2(t))$ and $C_{12} = \cos(\theta_1(t) + \theta_2(t))$. By differentiating Eq. (1) with respect to time, the relationship between the end-point velocity vector $\dot{\boldsymbol{x}}(t) \in \mathbf{R}^2$ and the joint angular velocity vector $\dot{\boldsymbol{\theta}}(t) \in \mathbf{R}^2$ is given as follows:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{J}(\boldsymbol{\theta}(t))\dot{\boldsymbol{\theta}}(t), \quad \ldots\ldots\ldots\ldots \quad (2)$$

where $\boldsymbol{J}(\boldsymbol{\theta}(t)) \in \mathbf{R}^{2\times 2}$ is a Jacobian matrix that represents the relationship between the end-point and joint spaces. The relationship between the joint torque vector $\boldsymbol{\tau}(t) \in \mathbf{R}^2$ and the end-point force vector $\boldsymbol{f}(t) \in \mathbf{R}^2$ is given by applying the principle of virtual work as follows:

$$\boldsymbol{\tau}(t) = \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{\theta}(t))\boldsymbol{f}(t). \quad \ldots\ldots\ldots\ldots \quad (3)$$

2.2. Relationship Between Muscle and Joint Spaces

The relationship between the muscle length vector $\boldsymbol{q}(t) \in \mathbf{R}^6$ and joint angle vector $\boldsymbol{\theta}(t) \in \mathbf{R}^2$ for the musculoskeletal system is given by the following equation:

$$\boldsymbol{q}(t) = \begin{bmatrix} \left\{(h_1 + a_1C_1 - s_1S_1)^2 \right. \\ \left. \quad + (d_1 - a_1S_1 - s_1C_1)^2\right\}^{\frac{1}{2}} \\ \left\{(h_2 - a_2C_1 - s_2S_1)^2 \right. \\ \left. \quad + (d_2 - a_2S_1 + s_2C_1)^2\right\}^{\frac{1}{2}} \\ \left\{(h_3 + a_3C_2 - s_3S_2)^2 \right. \\ \left. \quad + (d_3 - a_3S_2 - s_3C_2)^2\right\}^{\frac{1}{2}} \\ \left\{(h_4 - a_4C_2 - s_4S_2)^2 \right. \\ \left. \quad + (d_4 - a_4S_2 + s_4C_2)^2\right\}^{\frac{1}{2}} \\ \left\{(u_1 - L_1C_1 + u_3C_{12} - b_3S_{12})^2 \right. \\ \left. \quad + (b_1 - L_1S_1 - u_3S_{12} - b_3C_{12})^2\right\}^{\frac{1}{2}} \\ \left\{(u_2 - L_1C_1 + u_4C_{12} + b_4S_{12})^2 \right. \\ \left. \quad + (b_2 - L_1S_1 + u_4S_{12} - b_4C_{12})^2\right\}^{\frac{1}{2}} \end{bmatrix}, \quad . \ (4)$$

where $a_j, b_j, d_j, h_j, s_j, u_j$ $(j = 1, \ldots, 4)$ are the offsets for the muscular attachments. By differentiating Eq. (4) with respect to time, the relation between the muscle contractile vector $\dot{\boldsymbol{q}}(t) \in \mathbf{R}^6$ and the joint angular velocity vector $\dot{\boldsymbol{\theta}}(t) \in \mathbf{R}^2$ is given as follows:

$$\dot{\boldsymbol{q}}(t) = -\boldsymbol{W}^{\mathrm{T}}(\boldsymbol{\theta}(t))\dot{\boldsymbol{\theta}}(t), \quad (5)$$

where $\boldsymbol{W}(\boldsymbol{\theta}(t))$ is a Jacobian matrix that represents the relationship between the muscle and the joint spaces. The relationship between the joint torque vector $\boldsymbol{\tau}(t) \in \mathbf{R}^2$ and the muscular tensile force vector $\boldsymbol{\alpha}(t) \in \mathbf{R}^6$ is given by applying the principle of virtual work as follows:

$$\boldsymbol{\tau}(t) = \boldsymbol{W}(\boldsymbol{\theta}(t))\boldsymbol{\alpha}(t). \quad (6)$$

The inverse relation of Eq. (6) is obtained as follows:

$$\boldsymbol{\alpha}(t) = \boldsymbol{W}^{+}(\boldsymbol{\theta}(t))\boldsymbol{\tau}(t) + \left(\boldsymbol{I}_6 - \boldsymbol{W}^{+}(\boldsymbol{\theta}(t))\boldsymbol{W}(\boldsymbol{\theta}(t))\right)\boldsymbol{k}_e, \quad (7)$$

where $\boldsymbol{W}^{+}(\boldsymbol{\theta}(t)) \in \mathbf{R}^{6\times 2}$ is a pseudo-inverse matrix of $\boldsymbol{W}(\boldsymbol{\theta}(t))$, $\boldsymbol{I}_6 \in \mathbf{R}^{6\times 6}$ is an identity matrix, and $\boldsymbol{k}_e \in \mathbf{R}^6$ is an arbitrary vector. The second term of Eq. (7) lies in the null space of $\boldsymbol{W}(\boldsymbol{\theta}(t))$, and denotes the muscular internal force.

Substituting Eq. (3) into Eq. (7) yields the relationship between the muscular tensile force vector $\boldsymbol{\alpha}(t)$ and the end-point force vector $\boldsymbol{f}(t)$, which is given as follows:

$$\boldsymbol{\alpha}(t) = \hat{\boldsymbol{J}}(t)\boldsymbol{f}(t) + \left(\boldsymbol{I}_6 - \boldsymbol{W}^{+}(\boldsymbol{\theta}(t))\boldsymbol{W}(\boldsymbol{\theta}(t))\right)\boldsymbol{k}_e, \quad (8)$$

where

$$\hat{\boldsymbol{J}}(t) := \boldsymbol{W}^{+}(\boldsymbol{\theta}(t))\boldsymbol{J}^{\mathrm{T}}(\boldsymbol{\theta}(t)). \quad (9)$$

The matrix $\hat{\boldsymbol{J}}(t) \in \mathbf{R}^{6\times 2}$ denotes the relationship between the muscle and end-point spaces. Thereafter in this study, the matrix $\hat{\boldsymbol{J}}(t)$ assumes full rank during movement in order to target the range of the system which does not become a singular configuration.

3. Proposed Control Method

The control input $\boldsymbol{\alpha} \in \mathbf{R}^6$ of the new proposed controller linearly combines the feed-forward input $\boldsymbol{u}_f \in \mathbf{R}^6$ with the feedback input $\boldsymbol{u}_b(t-T) \in \mathbf{R}^6$. The combination method of each input is similar to a previous study by the authors [1]. However, the construction method of each input is strikingly different. In this proposed method, the feed-forward input $\boldsymbol{u}_f$ constructs the desired internal force and the gravity compensation term at the desired position. The feedback input $\boldsymbol{u}_b(t-T)$ constructs the task space proportional-integral-derivative (PID) controller, which includes the time delay. The control input, which considers an output limitation of the muscle is constructed by introducing a new variable parameter ν. The block diagram of the proposed control method is shown in **Fig. 2**.

The control input $\boldsymbol{\alpha} = [\alpha_1, \ldots, \alpha_6]^{\mathrm{T}}$ is given as follows:

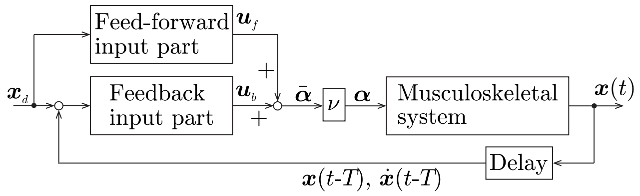

Fig. 2. Block diagram of the proposed control method.

$$\boldsymbol{\alpha}(t) := \begin{cases} \bar{\boldsymbol{\alpha}} & \text{if } \forall \alpha_i < \alpha_{\max} \\ \nu\bar{\boldsymbol{\alpha}} & \text{otherwise} \end{cases}, \quad (10)$$

$$\bar{\boldsymbol{\alpha}} = \boldsymbol{u}_f + \boldsymbol{u}_b(t-T), \quad (11)$$

where $\alpha_{\max}$ is the maximum muscular force, T denotes the time delay. The control inputs need to always satisfy the following equation, because the muscles can transmit tension only unidirectionally, when the transmit tension direction is the positive.

$$\bar{\alpha}_i \geq 0. \quad (12)$$

In this paper, the feed-forward input is given as to satisfy the condition.

3.1. Feed-Forward Input Part

The feed-forward input $\boldsymbol{u}_f$ of the proposed controller combines the muscular internal force [3–6] with the gravity compensation term at the desired position. This input $\boldsymbol{u}_f$ is given as follows:

$$\boldsymbol{u}_f = \left(\boldsymbol{I}_6 - \boldsymbol{W}^{+}(\boldsymbol{\theta}_d)\boldsymbol{W}(\boldsymbol{\theta}_d)\right)\boldsymbol{k}_e + \boldsymbol{W}^{+}(\boldsymbol{\theta}_d)\hat{\boldsymbol{g}}(\boldsymbol{\theta}_d), \quad (13)$$

where $\boldsymbol{\theta}_d = [\theta_{d1},\ \theta_{d2}]^{\mathrm{T}} \in \mathbf{R}^2$ is the desired joint angle, which corresponds to the desired end-point position $\boldsymbol{x}_d \in \mathbf{R}^2$ and $\boldsymbol{W}(\boldsymbol{\theta}_d) \in \mathbf{R}^{2\times 6}$ is the Jacobian matrix from the muscle to the joint space at the desired joint angle $\boldsymbol{\theta}_d$. $\boldsymbol{k}_e \in \mathbf{R}^6$ is the arbitrary vector, which is set as follows:

$$\boldsymbol{k}_e = \gamma\left[1.0,\ 1.0,\ 1.0,\ 1.0,\ 1.0,\ 1.0\right]^{\mathrm{T}}, \quad (14)$$

where $\gamma > 0$ is a positive constant. Namely, the first term of Eq. (13) is a constant vector.

In the muscular internal force feed-forward control method, the muscular internal force balancing at the desired position makes the potential field [3–6]. When the stable equilibrium point of the potential field is formed at the desired position, the motion of the musculoskeletal system converges at the desired position. The stable equilibrium point of the potential field is not necessarily formed at the desired position, because this potential field is a non-linear function that depends on muscular structure of the musculoskeletal system. The stability of the muscular internal force feed-forward control method is not the gist of this paper and it has been reported in other paper [6]. This paper focuses on the muscular structure, which is formed at the stable equilibrium point of the potential field at the desired position. The parameters of the musculoskeletal system are listed in **Tables 1** and **2**.

$\hat{\boldsymbol{g}}(\boldsymbol{\theta}_d)$ is the gravity compensation term including errors of physical parameters (the mass of links and the cen-

Table 1. Physical parameters of the musculoskeletal system.

	Link 1	Link 2
Mass [kg]	1.439	1.089
Length [m]	0.315	0.234
Center of mass position [m]	0.147	0.119
Inertia moment [kgm^2]	0.011	0.004
Joint viscosity [Ns/rad]	1.0	1.0

Table 2. Muscular arrangement of the musculoskeletal system.

j	1	2	3	4
a_j [mm]	120	120	120	120
b_j [mm]	20	20	20	20
d_j [mm]	20	20	20	20
h_j [mm]	50	50	50	50
u_j [mm]	50	50	50	50
s_j [mm]	10	10	10	10

ter of mass position), which is given as follows:

$$\hat{\boldsymbol{g}}(\boldsymbol{\theta}_d) = \begin{bmatrix} \hat{m}_1 g \hat{l}_{g1} \cos\theta_{d1} + \hat{m}_2 g L_1 \cos\theta_{d1} \\ \qquad + \hat{m}_2 g \hat{l}_{g2} \cos(\theta_{d1}+\theta_{d2}) \\ \hat{m}_2 g \hat{l}_{g2} \cos(\theta_{d1}+\theta_{d2}) \end{bmatrix}, \quad (15)$$

where g is the gravitational acceleration. $\hat{m}_n$ $(n = 1,2)$ is the mass of the link including errors and $\hat{l}_{gn}$ is the center of gravity of the link including errors. In reality, accurate values of these parameters are difficult to obtain and likely to contain errors. The second term of Eq. (13) is the constant vector, which compensates for the gravity at the desired position and is not estimated online. Therefore, this feed-forward input $\boldsymbol{u}_f$ is the constant vector.

3.2. Feedback Input Part

The feedback input $\boldsymbol{u}_b(t-T)$ is designed by a PID feedback controller with the inclusion of the time delay as follows:

$$\boldsymbol{u}_b(t-T) = -\hat{\boldsymbol{J}}^{\mathrm{T}}(t-T)\left\{\boldsymbol{K}_p \Delta\boldsymbol{x}(t-T) + \boldsymbol{K}_v \dot{\boldsymbol{x}}(t-T) + \boldsymbol{K}_i \int_0^t \Delta\boldsymbol{x}(\tau-T) d\tau\right\}, \quad (16)$$

where $\boldsymbol{K}_p \in \mathbf{R}^{2\times2}$, $\boldsymbol{K}_v \in \mathbf{R}^{2\times2}$, and $\boldsymbol{K}_i \in \mathbf{R}^{2\times2}$ are the feedback gain matrices. $\Delta\boldsymbol{x}(t) \in \mathbf{R}^2$ is the end-point position error vector from the desired end-point position vector $\boldsymbol{x}_d$ as follows:

$$\Delta\boldsymbol{x}(\tau-T) = \boldsymbol{x}(\tau-T) - \boldsymbol{x}_d. \quad (17)$$

The matrix $\hat{\boldsymbol{J}}$ includes the time delay T, composed of sensory information obtained by a camera. Namely, the feedback input $\boldsymbol{u}_b(t-T)$ includes the time delay.

Table 3. Physical parameters used in the control input.

	Link 1	Link 2
Mass [kg]	1.678	0.950
Center of mass position [m]	0.158	0.117

3.3. Definition of Variable Parameter ν

Generally, the actuator is set to an output limit. In the proposed controller, the movement to the desired position is achieved by balancing each muscular force. When one of the muscular forces is saturated by exceeding the output limit, there is a possibility that the musculoskeletal system performs unexpected movements. Therefore, the variable parameter ν, which prevents saturation at the output limit, is introduced.

Tahara et al. [2] proposed a control method considering the output limit for the musculoskeletal system. This control method defined the parameter without renewing online, assuming that the control input $\boldsymbol{\alpha}$ does not become larger than the feed-forward input $\boldsymbol{u}_f$ during movement. However, there is a possibility that the control input $\boldsymbol{\alpha}$ becomes larger than the feed-forward input $\boldsymbol{u}_f$ due to gain settings and unexpected behaviors of the system. In this paper, the variable parameter ν is designed as follows:

$$\nu = \frac{\alpha_{\max}}{\max[\boldsymbol{\alpha}]}, \quad (18)$$

where $\alpha_{\max}$ is the maximum muscular force. The variable parameter ν acts to reduce the muscular force within the output limit, while keeping the conditions of balance for each muscular force, when the value over the maximum muscular force is $\alpha_{\max}$.

4. Numerical Simulation

In this section, the effectiveness of the proposed control method is confirmed through several numerical simulations. The simulations are conducted to demonstrate that the reaching movement of the musculoskeletal system occurs as shown in **Fig. 1**. **Table 1** lists the physical parameters of the musculoskeletal system, **Table 2** lists the muscular arrangement of the musculoskeletal system, and **Table 3** lists the physical parameters including the error using calculations of the control input. The physical parameters of the musculoskeletal system as summarized in **Table 1** are set by using the physical parameters estimating method of human [22]. **Table 3** lists the actual values that are randomly selected from a set of error rates 20% of the true value, displayed in **Table 1**.

In the numerical simulations, the proposed controller is compared with the feed-forward controller without considering the parameter ν, as shown in Eq. (13). The time delay T of the sensory information is set to $T = 300$ ms. The feed-forward controller does not consider the variable parameter ν to show the effectiveness of this parameter, which is introduced anew in the proposed method. The

Table 4. Initial and desired positions (swing-up motion).

Initial position [m]	$\boldsymbol{x}_0 = [-0.2,\ 0.2]^{\mathrm{T}}$
Desired position [m]	$\boldsymbol{x}_d = [0.0,\ 0.4]^{\mathrm{T}}$

Table 5. Each gain (swing-up motion).

	Proposed controller	FF controller
γ	125	150
$\boldsymbol{K}_p$	diag[1.7, 1.7]	–
$\boldsymbol{K}_v$	diag[0.8, 0.8]	–
$\boldsymbol{K}_i$	diag[4.0, 4.0]	–

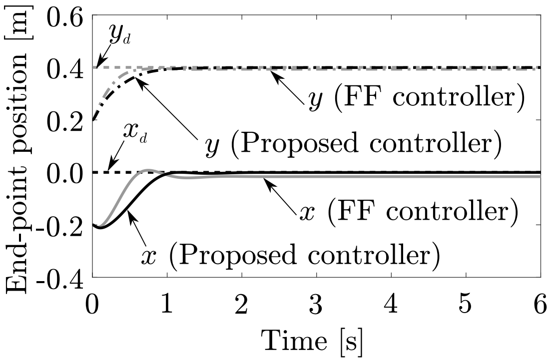

Fig. 3. Transient response of the end-point position when comparing the proposed controller with the feed-forward controller (swing-up motion).

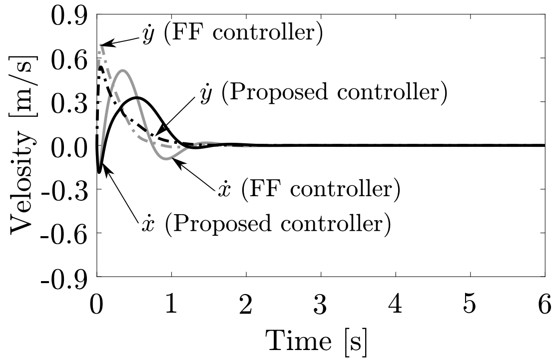

Fig. 4. Transient response of the end-point velocity when comparing the proposed controller with the feed-forward controller (swing-up motion).

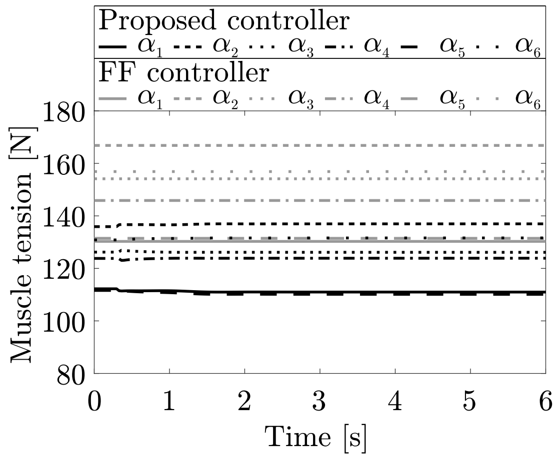

Fig. 5. Transient response of the control input when comparing the proposed controller with the feed-forward controller (swing-up motion).

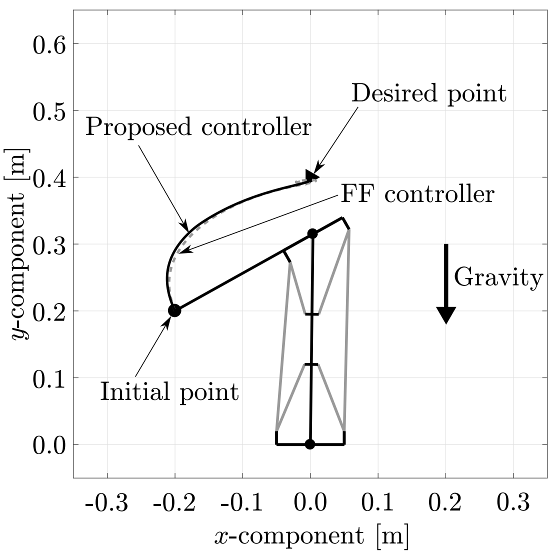

Fig. 6. Loci of the end-point position in the task space (swing-up motion).

feedback controller including the time delay is not used as a comparison target, because this controller is confirmed that it was unstable in previous research [1].

4.1. Swing-Up Motion Under the Effect of Gravity

Simulations performed the swing-up motion under the effect of gravity. The initial and desired positions of the end-point are shown in **Table 4** and each gain used in the simulation is shown in **Table 5**. The gains of the controllers were chosen such that the 5% setting times of all the results were equal.

Figure 3 shows the transient responses of the end-point position, **Fig. 4** shows the transient responses of the end-point velocity, **Fig. 5** shows the transient responses of the control input, and **Fig. 6** shows the loci of the end-point position in the task space. **Figs. 3**, **4**, and **6** show that the end-point trajectory exhibits slight differences in case of using the feed-forward controller. The reason for this result is that the effect of the gravity cannot be accurately compensated because the physical parameters include errors.

In contrast, **Figs. 3**, **4**, and **6** show that the movement of the system converge on the desired position in case of using the proposed controller. The reason for this result is that the end-point position moves the periphery of the desired position by the feed-forward input and the devi-

Table 6. Initial and desired positions (swing-down motion).

Initial position [m]	$\boldsymbol{x}_0 = [0.2,\ 0.4]^{\mathrm{T}}$
Desired position [m]	$\boldsymbol{x}_d = [-0.2,\ 0.2]^{\mathrm{T}}$

Table 7. Each gain (swing-down motion).

	Proposed controller	FF controller
γ	110	150
$\boldsymbol{K}_p$	diag[22, 22]	-
$\boldsymbol{K}_v$	diag[3.6, 3.6]	-
$\boldsymbol{K}_i$	diag[14, 14]	-

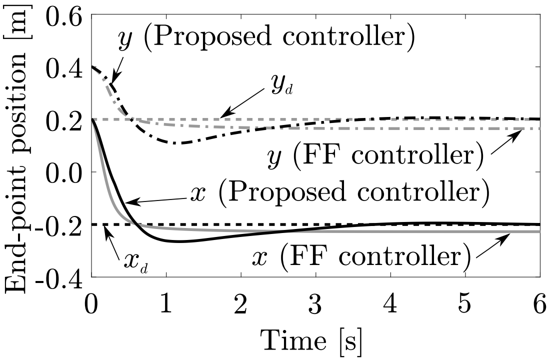

Fig. 7. Transient response of the end-point position when comparing the proposed controller with the feed-forward controller (swing-down motion).

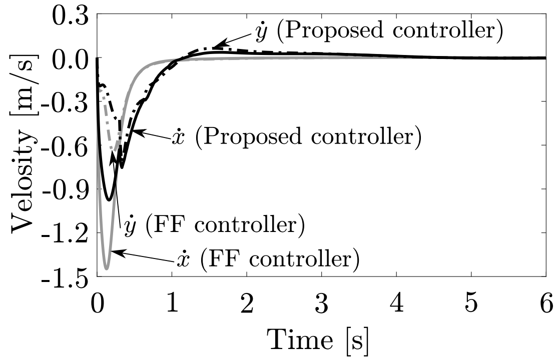

Fig. 8. Transient response of the end-point velocity when comparing the proposed controller with the feed-forward controller (swing-down motion).

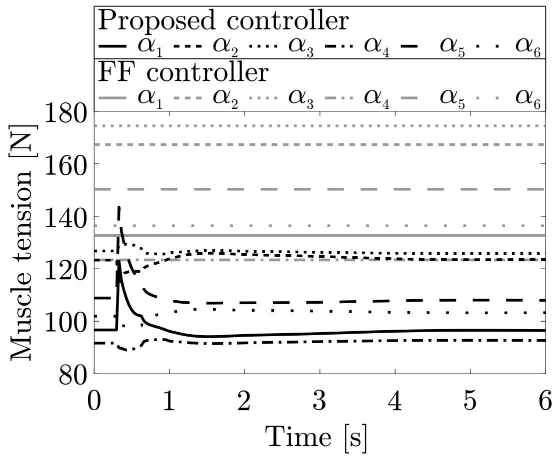

Fig. 9. Transient response of the control input when comparing the proposed controller with the feed-forward controller (swing-up motion).

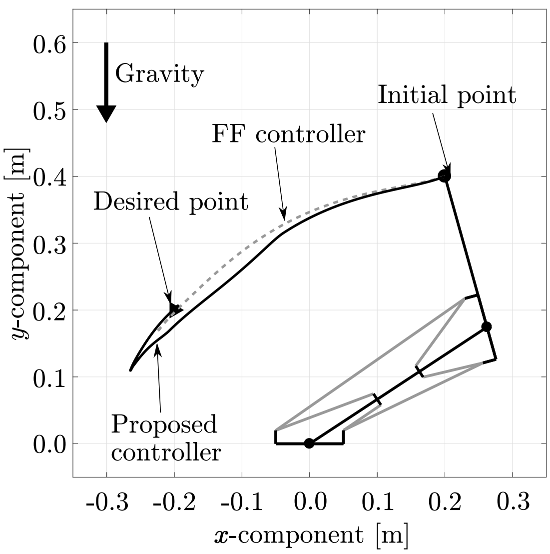

Fig. 10. Loci of the end-point position in the task space (swing-down motion).

ation of the end-point is reduced by an integral term of the feedback input. When comparing the control input, as shown in **Fig. 5**, the proposed controller can achieve the reaching movement by a smaller control input compared to the feed-forward controller. The reason for this result is that even a small control input can generate the joint torque, equivalent to the joint torque of the feed-forward controller, by increasing the muscular force of agonist muscles and decreasing the muscular force of antagonist muscles by using the PD term.

4.2. Swing-Down Motion Under the Effect of Gravity

Subsequently, the simulation performed the swing-down motion under the effect of gravity. The initial and desired positions of the end-point are shown in **Table 6** and each gain used in the simulation is shown in **Table 7**. The gains of the controllers were chosen such that the 5% setting times of all the results were equal.

Figure 7 shows the transient responses of the end-point position, **Fig. 8** shows the transient responses of the end-point velocity, **Fig. 9** shows the transient responses of the control input, and **Fig. 10** shows the location of the end-point position in the task space. **Figs. 7**, **8**, and **10** show that the end-point does not converge on the desired position in case of using the feed-forward controller. The

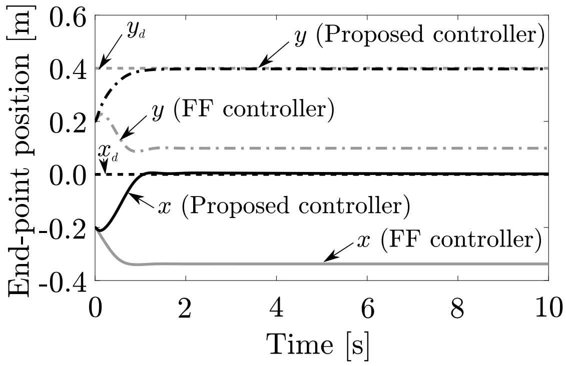

Fig. 11. Transient response of the end-point position when comparing the proposed controller with the feed-forward controller in the case of considering the output limit.

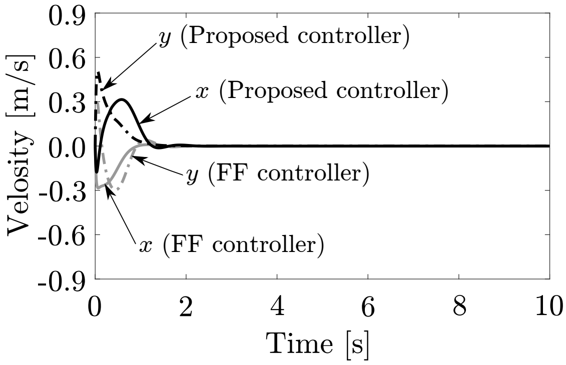

Fig. 12. Transient response of the end-point velocity when comparing the proposed controller with the feed-forward controller in the case of considering the output limit.

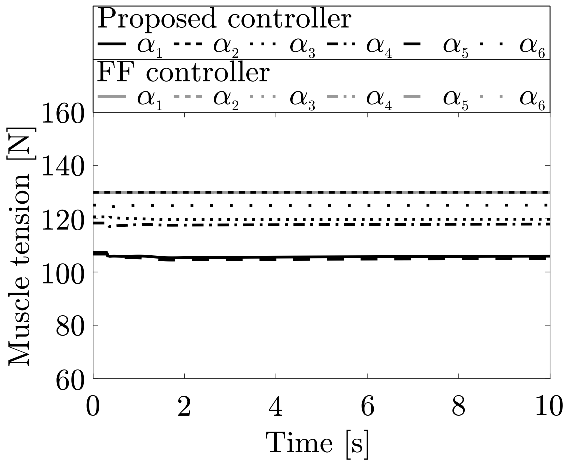

Fig. 13. Transient response of the control input when comparing the proposed controller with the feed-forward controller in the case of considering the output limit.

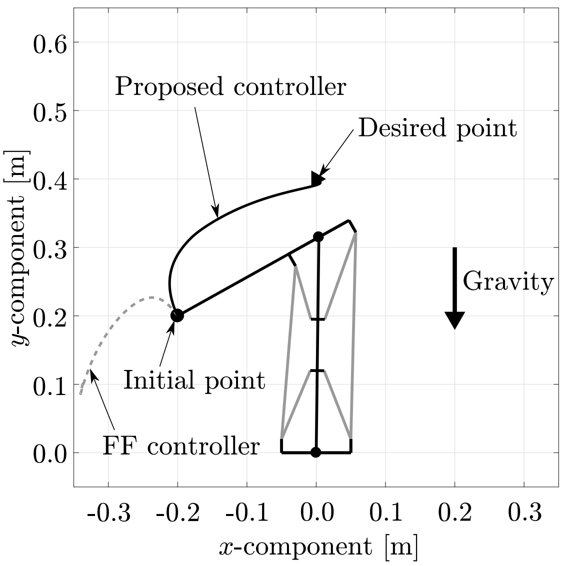

Fig. 14. Loci of the end-point position on the task space in the case of considering the output limit.

overshoot of the end-point may be caused by the inertial force of the movement.

In contrast, the movement of the system converges on the desired position in case of using the proposed controller. However, the overshoot of the end-point occurs during the movement. The reason for this result is the effect of the inertial force of the movement. The end-point may be tardily compensated using the feedback input, including the time delay.

4.3. Swing-Up Motion in Consideration of the Output Limit

The simulation performed the swing-up motion under the effect of gravity, while considering the output limit. The maximum muscular force $\alpha_{\max}$ is set to $\alpha_{\max} =$ 130 N. The simulation results show that the musculo-skeletal system remains stable even without re-setting the gain parameters, because the variable parameter ν is introduced into the proposed method. Therefore, the simulation used the same parameters listed in **Tables 4** and **5**.

Figure 11 shows the transient responses of the end-point position, **Fig. 12** shows the transient responses of the end-point velocity, **Fig. 13** shows the transient responses of the control input, and **Fig. 14** shows the location of the end-point position in the task space.

Figures 11–**14** show that the end-point does not converge on the desired position because each muscular force do not balance when using the feed-forward controller. In contrast, the end-point position converges on the desired position because the proposed method can reduce the muscular force within the output limit while keeping the condition of balance of each muscular force. The response of the end-point deteriorates because the muscular force gets smaller. The system does not experience runaway when the control input is not saturated during movement in the proposed method, even if the output limit is not known or if the gain of the simulation is used in an experiment. This advantage is gained in the proposed method by using the variable parameter ν.

5. Conclusions

This paper discussed the reaching movement of the musculoskeletal system under gravity, and proposed a novel control method for the musculoskeletal system that combines feed-forward with feedback input. The input of the proposed controller can be constructed by combining the muscular internal force feed-forward control with a task-space PID controller, which includes the time delay without requiring a dynamical model, accurate physical parameters, or accurate sensory information. The effectiveness of the proposed method was demonstrated by the results of numerical simulations. The proposed controller achieved the reaching movement of the musculoskeletal system without requiring accurate physical parameters for gravity and without saturation with the output limit. As future work, the practicability of the proposed controller will be demonstrated by conducting experiments. In this paper, the physics parameter errors were set to 20%, because large errors are supposed to be prevented using the parameter identification method. However, the permissible range of the errors must be verified in the future. In addition, the permissible range of the errors considering the dynamic characteristic will be discussed, because the convergence of the system is not good when the error becomes large.

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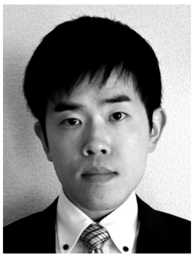


Name:

Yuki Matsutani

Affiliation:

Assistant Professor, Department of Robotics, Faculty of Engineering, Kindai University

Address:

1 Takaya Umenobe, Higashi-hiroshima, Hiroshima 739-2116, Japan

Brief Biographical History:

2015 Received Ph.D. in Engineering from Kyushu University

2015-2019 Assistant Professor, Department of Mechanical and Intelligent Systems Engineering, National Institute of Technology, Kumamoto College

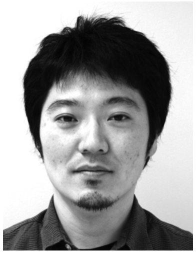
2019- Assistant Professor, Department of Robotics, Faculty of Engineering, Kindai University

Main Works:

• "Complementary compound set-point control by combining muscular internal force feedforward control and sensory feedback control including a time delay," Advanced Robotics, Vol.32, No.8, pp. 411-425, 2018.

Membership in Academic Societies:

• The Institute of Electrical and Electronics Engineers (IEEE)
• The Robotics Society of Japan (RSJ)
• The Japan Society of Mechanical Engineers (JSME)



Name:
Kenji Tahara

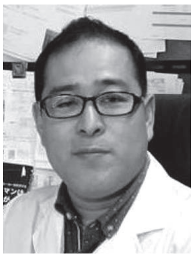
Affiliation:
Associate Professor, Department of Mechanical Engineering, Faculty of Engineering, Kyushu University

Address:
744 Moto'oka, Nishi-ku, Fukuoka 819-0395, Japan

Brief Biographical History:
2003 Received Ph.D. in Robotics from Ritsumeikan University
2003-2007 Research Scientist, The Institute of Physical and Chemical Research (RIKEN)
2007-2011 Research Associate Professor, Kyushu University
2011- Associate Professor, Department of Mechanical Engineering, Kyushu University

Main Works:
- "Bio-mimetic pinching movements of musculo-skeletal dual finger model," Advanced Robotics, Vol.25, Nos.1-2, pp. 175-204, 2011.

Membership in Academic Societies:
- The Institute of Electrical and Electronics Engineers (IEEE)
- The Society of Instrument and Control Engineers (SICE)
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)



Name:
Hitoshi Kino

Affiliation:
Professor, Department of Intelligent Mechanical Engineering, Faculty of Engineering, Fukuoka Institute of Technology

Address:
3-30-1 Wajirohigashi, Higashi-ku, Fukuoka 811-0295, Japan

Brief Biographical History:
1994 Received B.S. in Engineering from Ritsumeikan University
1996 Received M.S. in Engineering from Ritsumeikan University
2000 Received Ph.D. in Engineering from Ritsumeikan University
2001-2003 Lecturer, Fukuoka Institute of Technology
2003-2011 Associate Professor, Fukuoka Institute of Technology
2011- Professor, Fukuoka Institute of Technology

Main Works:
- "Inverse Dynamics of Human Passive Motion Based on Iterative Learning Control," IEEE Trans. on Systems, Man, and Cybernetics, Part A, Vol.42, No.2, pp. 307-315, 2012.
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Membership in Academic Societies:
- The Institute of Electrical and Electronics Engineers (IEEE)
- The Robotics Society of Japan (RSJ)
- The Japan Society of Mechanical Engineers (JSME)