Simultaneous Control Framework for Humanoid Tracking Human Movement With Interacting Wearable Assistive Device

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Simultaneous Control Framework for Humanoid Tracking Human Movement with Interacting Wearable Assistive Device

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***Abstract*— Instead of human subjects, humanoid robots can be used as human dummies to test the human-designed products. We propose a controller that uses wearable assistive devices (also referred to as exoskeletons) to reproduce human movement in the evaluation. The proposed control scheme consists two components: one is the torque controller designed for a simplified interaction model with the device, and the other is the tracking controller based on a vector field to reproduce human motion. We implemented the proposed controller on the human-sized humanoid HRP-4 and validated the feasibility of the human motion reproduction by wearing the assistive device. In the experiment, we tested the commercially available device "Muscle Suit" by using our control scheme. The experimental results showed that while the device applies its supporting strength, the humanoid robot could reproduce human movements. The assistive effect of the device was visualized effectively in our evaluation framework.**

I. INTRODUCTION

Japan is a super-aged company that faces the problem of the elderly and country's national caregiver shortage. Robot technology is expected to be one clue for solving this social problem under this social background. There are several researches about various robotic assistive devices such as the device for walking [1], [2], for monitoring one's health [3], for manipulating heavy objects [4], [5], for reducing caregiver load [6], and for rehabilitations [7], [8]. Exoskeletons, lightweight and easy-to-wear tools among them in particular, are a promising option not only for caregivers but also for any worker who performs heavy load tasks to reduce stress on the lower back. Some commercial products of exoskeletons are already available [9], [10], [11]. The market of exoskeletons is now exploding and thus requires a method to test the different commercial products quantitatively to let the users compare them. Currently, the common method is an evaluation by using a questionnaire which is filled by users, measuring contact pressure between a human body and a device or muscle activity through the surface electromyogram (EMG) signals [12]. However, such a method has several limitations; a questionnaire is qualitative and difficult to compare the products of different companies, the ethical restrictions or injury risk avoidance have to be considered in human experiments, and the evaluation often lacks the repeatability of results. An alternative method is modeling the human body and simulating the motion by using a dynamic simulator [13]. Although the human simulation can estimate information inside the human body quantitatively, it requires precise dynamic modeling of the human body and the device. The contact situation between the human body and the device is also difficult to simulate.

Some works have introduced the evaluation method of assistive devices by using a humanoid robot instead of human experiments (see [14], [15], [16]). Such an evaluation needs the reproduction of human whole-body movements by a robot. The human motion reproduction on humanoid robot has been proposed in [17], [18], [19]. In these papers, a reference human motion is given to a humanoid robot as a time-dependent trajectory so that the robot can reproduce the same motion that humans did by using typical joint PD controllers. Nevertheless, in the case of imitating a movement that interacts with environments such as the use of active assistive devices (i.e., devices with actuators), the tracking control might fail due to the conflict between the control system of the robot and that of the device. There are the approaches to generate a time-independent trajectory by using non-linear dynamical system developed in [20], [21]. These methods allow an interactive motion reproduction by feeding back the robot actual state and modulating the original trajectory [22]. However, there is still room for an interaction to be designed so that a robot can reproduce a human motion in the same way as a human. In our previous research [23], we introduced the tracking control by using torque feedback. In that paper, we introduced a low-dimensional model as a reference of interaction between a robot and a device and realized human motion reproduction by a humanoid. However, the control scheme assumes that the low-dimensional model requires the one-to-one correspondence between the trajectory and the whole-body posture, so that the same body posture cannot be repeated in the same motion trajectory. Therefore, the previous control scheme cannot apply to the motion repeating the same postures like circle motions.

In this paper, we propose a new control scheme that solves the above issue and allows the controller to reproduce the complex motion. In the proposed control scheme, the two components are introduced: the external torque observer that estimates the assistive torque from an assistive device, and the tracking controller that reproduces human motion while achieving the desired interaction between a robot and a device based on the estimated external force. The combination of the two components finally generates the human-like whole-body movement of the robot according to

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the assistive forces applied by the device. We have conducted the experiments to validate the proposed control scheme by humanoid HRP-4 [24] with wearable assistive device Muscle Suit [9]. We also check whether the proposed method can extract the assistive effect of the device quantitatively.

This paper is organized as follows: Section II presents the details of the new control system. Section III presents the experimental validation of the control scheme and the case study of testing the assistive effect by the proposed method. Finally, we conclude the paper with several remarks.

II. Our new Controller

We present the control framework for tracking a trajectory with interacting an active assistive device, considering following assumptions of the human behavioral intention when using the assistive device. The assistive device is often designed for the human body to support a typical task such as lifting an object. As a result, human motion is likely to follow an identical trajectory due to a geometric constraint of the mechanical structure of the device. Most devices can generate high assistive force to reduce human muscle effort. We assume that human muscles exert less forces when utilizing the device at assisted parts of human body. In fact, we have shown that the muscle effort when assisted by the device is similar to when it is relaxed, through the EMG signals analysis on the human subject experiment [25].

Achieving that a humanoid reproduces human motion when using an assistive device, the humanoid has to track the human motion trajectory in response to the external force applied by the device. We show an overview of our control framework in Fig. 1. The controller comprises two components; the torque observer that estimates an assistive torque and the tracking controller that achieves motion reproduction with desired interaction. Combining these components, the tracking controller can compute the desired joint angles of the robot under consideration of the external torque to avoid the torque confliction between the robot and the device. With this controller, we can realize human motion reproduction on the humanoid robot in a similar interaction situation to that of humans. To create the target trajectory, we captured the human motion with a device and generate the feasible trajectory for humanoid by using the motion retargeting technology [26]. Based on our previous controller [23], we introduce the single phase parameter x that represents all the joint angle trajectories $\boldsymbol{\theta}$ of a robot when the robot tracks the trajectory.

$$\tau_{joint} + \tau_{ast} = f(x) \triangleq h(\boldsymbol{\theta}(x), \dot{\boldsymbol{\theta}}(x), \ddot{\boldsymbol{\theta}}(x)), \tag{1}$$

where τ_{joint} and τ_{ast} are the joint torque and external torque applied by an assistive device, respectively, and $f(x)$ or $h(\boldsymbol{\theta}(x), \dot{\boldsymbol{\theta}}(x), \ddot{\boldsymbol{\theta}}(x))$ is the torque coming from the inertial, Coriolis, and gravity forces.

The trajectories $\theta_{(x)}$ and the derivatives are designed according to the measured data of human motion by motion retargeting technology. In this research, we use the efficient motion retargeting method proposed in [26]. Here, we briefly explain the features of this method. Considering

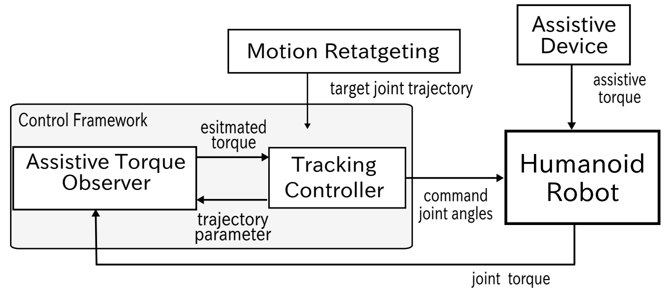

Fig. 1. Overview of our controller

the differences of the body structures between the robot and humans, the method solves a simultaneous optimization problem, including the following three sub-problems:

1) Inverse kinematics problem that calculates the joint angle trajectories of a human model to achieve the measured motion.
2) Problem of identifying the morphing function between the human and robot models.
3) Motion-planning problem that considers physical consistency of the robot such as a balance or joint limits.

The humanoid motion is obtained as a result of the above optimization problem. Since the method involves the motion-planning problem, that trajectory of a humanoid can be achieved with no additional controllers. The method shown in [26] can also realize the inverse motion retargeting from humanoid to human, which can estimate the human motion reflecting the modification happened in the forward motion retargeting. Though the direct comparison between the dynamics of the human and that of the robot is difficult, the reproducibility about the motion retargeting can be quantified by comparing the difference between the original human motion and the estimated human motion. The detail of the evaluation is shown in [26].

We first present the external torque observer in Section II-A. Then, we present the tracking control scheme in II-B.

A. External Torque Observer

Fig. 1 shows the summary of our controller. First, the external torque observer is presented for the estimation of the assistive torque. The tracking controller adjust x by using the estimated torque in order to achieve the desired interaction. In this paper, we utilize the momentum based disturbance observer detailed in [27], [28]. The dynamics can be written as a transfer function when adding the residual value r.

$$\frac{r}{\tau_{joint}} = \frac{K}{s+K}, \tag{2}$$

where s is a Laplacian operator, K is observer gain ($K > 0$) and τ_{joint} is a joint torque in Eq. (1). We can formulate the first order differential equation of r from Eq. (2):

$$\dot{r} = -Kr + K\tau_{joint}, \tag{3}$$

Since the assistive torque cannot be measured directly, we observe the residual value r as $f_{(x)} - \tau_{ast}$ in Eq. (1).

Replacing r with $f_{(x)} - \tau_{ast}$, Eq. (3) can be written via τ_{ast}

$$\dot{\tau}_{ast} = -K\tau_{ast} + K(f(x) + \tau_{joint}) - \dot{f}_{(x)}, \tag{4}$$

From above equation, we can track the evolution of the external torque τ_{ast} during the motion. Practically, we discretize Eq. (3) and reformulate as:

$$\begin{aligned}\hat{\tau}_{ast}[t+1] &= (1 - K\Delta t)\hat{\tau}_{ast}[t] \\ &+ K\Delta t(f(x[t]) + \tau_{joint}) - \dot{f}_{(x[t])},\end{aligned} \tag{5}$$

where $\hat{\tau}_{ast}$ is an estimated assistive torque and Δt is a time step of a controller. $\dot{f}_{(x)}$ is derivative of $f_{(x)}$, computed in the following controller:

B. Tracking Controller based on External Torque

The observer gives the assistive torque to the tracking controller. Then, the tracking controller adjusts the parameter x to achieve human motion reproduction. We call the space expressed in the parameter x and torque τ as x-τ interaction space and the state is written as (x, τ). Adjusting x in response to the estimated torque $\hat{\tau}_{ast}$, we designed an interaction model in $x - \tau$ space. According to our assumption, the desired interaction is achieved when the assisted joint torque is equal to be zero ($\tau_{joint} = 0$), which is equivalent to $\tau_{ast} = f_{(x)}$. We computed the reference torque trajectory $f^{trg}_{(x)}$ that is required to realize the given motion without using an assistive device. Therefore, the controller computes desired x (x^{des}) in such a way as to satisfy $\hat{\tau}_{ast} = f^{trg}_{(x)}$. However, when the multiple values of x^{des} satisfying $\hat{\tau}_{ast} = f^{trg}_{(x)}$ exist, the controller cannot compute unique x^{des}, which is the case that trajectory does not have the one-to-one correspondence between x and $f_{(x)}$. In these cases, the computation of x is indeterministic due to the singularity, and causes the instability of the controller. To solve this problem, we design the vector field to attract current x to the nearest x^{des} so that the controller can achieve the nearest x^{des}.

We introduce the tracking control based on a vector field in x-τ space as shown in Fig. 2. Fig. 2 shows an example of the reference torque trajectory (blue solid line) when a humanoid reproduces the lif-up motion with an assistive device; a vertical axis denotes normalized $\hat{\tau}_{ast}$ and a lateral axis denotes normalized x corresponding to a humanoid posture. The vector field is designed to attract the current state of $(x, \hat{\tau}_{ast})$ to the desired state $(x^{des}, \hat{\tau}_{ast} = f^{trg}(x^{des}))$ by giving a velocity of x. Therefore, the vector field is represented below function:

$$\dot{x} = V(x,\ \hat{\tau}_{ast}). \tag{6}$$

Here, we can also compute $\dot{\hat{\tau}}_{ast}$ in same as $\dot{x}$. $\dot{\hat{\tau}}_{ast}$ is a change of the torque due to a change of x. Therefore, we assume $\dot{\hat{\tau}}_{ast} = \dot{f}_{(x)}$ while $\tau_{joint} \simeq 0$ in Eq. (1) and we utilize $\dot{\hat{\tau}}_{ast}$ as $\dot{f}_{(x)}$ in Eq. (4).

The procedure of the vector field creation is follows: The reference trajectory $\boldsymbol{f^{trg}_{(x)}}$ can be computed by inverse dynamics computation using target trajectory $(\boldsymbol{\theta}(x), \dot{\boldsymbol{\theta}}(x), \ddot{\boldsymbol{\theta}}(x))$

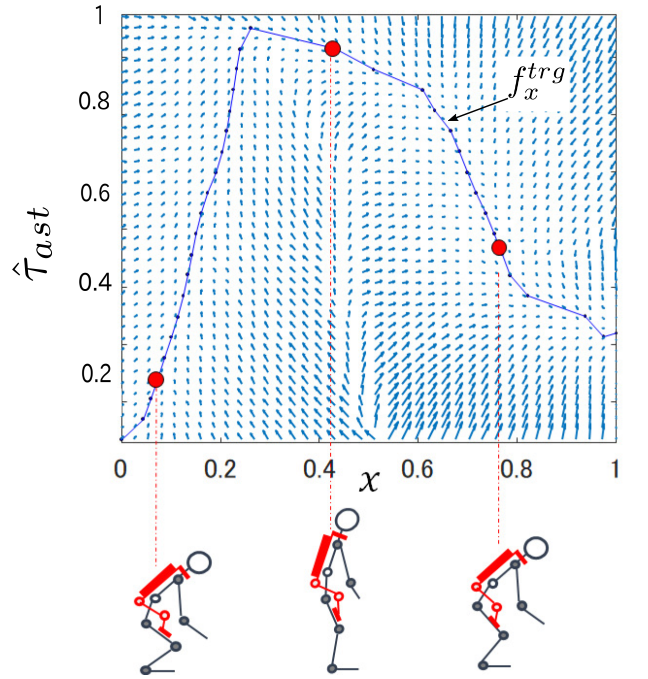

Fig. 2. Relationship between the desired state $(x, f_{(x)})$ in the interaction model and a current robot state $(x, \hat{\tau}_{ast})$ with the vector field. The solid line is the target trajectory $f^{trg}_{(x)}$ generated by the motion retargeting method and the arrows denote the gradient vectors at each point in the space.

generated by motion trajectory method. $\boldsymbol{f^{trg}_{(x)}}$ is given as a sequence data including n size data set ($f^{trg}_{(x)} = [f^{trg}_{(x[1])} f^{trg}_{(x[2])}, ..., f^{trg}_{(x[i])}, ..., f^{trg}_{(x[n])}]$). Now, we assume a target trajectory as $\boldsymbol{a}$:

$$\begin{aligned}\boldsymbol{a} &= [\boldsymbol{a_1}, ...\boldsymbol{a_i}, ..., \boldsymbol{a_n}] \\ &= [(x[1], f^{trg}_{(x[1])}), ..., (x[i], f^{trg}_{(x[i])}), ..., (x[n], f^{trg}_{(x[n])})].\end{aligned} \tag{7, 8}$$

then, a vector $V_c(x, \hat{\tau}_{ast})$ at a point $\boldsymbol{c}$ is determined by following procedure:

1) find the closest point $\boldsymbol{a_i}(x[i], f^{trg}_{x[i]})$, from a point $\boldsymbol{c}$ in $\boldsymbol{a}$ as shown in Fig. 3;
2) compute a vector from a current point $\boldsymbol{c}$ to $\boldsymbol{a_i}$ that pulls in the trajectory, and a vector from $\boldsymbol{a_i}$ to $\boldsymbol{a_{i+1}}$ that is a flow to the next state;
3) compose two vectors and compute $V_c(x, \hat{\tau}_{ast})$ by

$$V_C(x,\ \hat{\tau}_{ast}) = K_v(a_i - c) + K_v(a_{i+1} - a_i). \tag{9}$$

Applying the above procedure over all points in the space, the vector field can be obtained as shown in Fig. 2. From the vector field, $\dot{x}[t+1]$ is given by the vector $V(x[t], \hat{\tau}_{ast})$ at each control period t:

$$\dot{x}[t+1] = V(x[t], \hat{\tau}_{ast}[t]) \tag{10}$$

The above control framework realizes that a humanoid robot tracks the human motion trajectory while its joint is fully supported by the assistive device. The following section provides an experimental validation of our controller and an evaluation of the assistive device by using the controller.

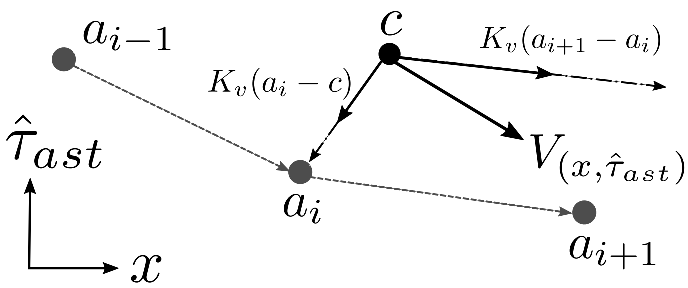

Fig. 3. Defining the vector at the point $C(x, \hat{\tau}_{ast})$. $x, \hat{\tau}_{ast}$ are current state, $f^{trg}_{(x[i])}$ is the closest point of trajectory from C, $i = 1, 2, ..., n$.

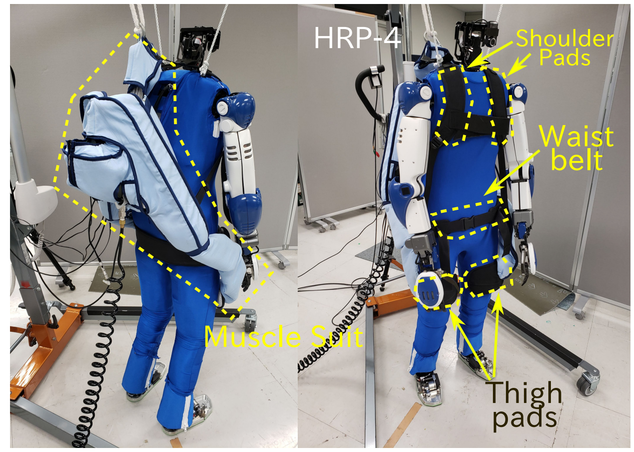

Fig. 4. Humanoid robot HRP-4 and Muscle Suit. The device is attached on shoulders, waist, and thighs in exactly the same way as a human does.

III. Experiments on Humanoid

We tested the proposed controller with a human-sized humanoid robot and a commercialized assistive device Muscle Suit. We first validate whether the controller can be applied to the motion trajectory. We chose to lift an object up and down motion as a typical task when using the assistive device for supporting lower back. It is also checked whether the assistive torque of the device can be extracted quantitatively by using our controller through our evaluation framework.

A. Experimental Setup

The experiments were conducted with humanoid HRP-4 [24], the Muscle Suit [6], [29] that is driven by pneumatic actuators and designed for reducing the human lower back load during lifting a heavy object. The humanoid robot has 37 degrees of freedom in total and its weight and height is approximately 40 kg and 155cm, respectively. The geometric parameters of the robot are designed based on that of the average Japanese female, detailed in [24]. The robot has a soft cover so that a wearable assistive device can be attached without modification.

Fig. 4 shows HRP-4 wearing the Muscle Suit. The robot can wear the device in exactly the same way as a human does: wearing on shoulders, attaching with the waist belt and thigh pads. The interface of the device is a touch switch or an exhalation switch, which controls the supply of the compressed air for driving the pneumatic actuators.

We captured the human motion which represents the target trajectory in our control framework. In the measurement experiment, we used the motion capture system (Motion Analysis) and recorded the motion trajectory of a human subject lifting a 5 kg weight; the subject wearing Muscle Suit bends down to catch the weight, lifts it up, and puts it down. The recorded motion was retargeted to the feasible trajectory of the humanoid robot by using the motion retargeting method detailed in [26]. The vector field used in the controller was generated from the retargeted trajectory by using the creation procedure mentioned in II-B. Since the retargeted trajectory is generated with taking into account the joint limits or balancing, the robot can reproduce the motion without extra controllers.

B. Experimental Validation of Proposed Controller

We tested our controller on HRP-4 with the Muscle Suit by using the proposed controller. In this experiment, we attached the 4-kg weight to the wrist joints of the robot (2 kg to each wrist) in advance to avoid executing the object grasping task. The robot postures reproduced by the proposed controller are shown in Fig. 5. The humanoid was first crouched with its waist bending (posture (a)), and then the robot started lift-up motion (posture(b-c))when the device was activated and starts supporting the waist joint. After the lifting-up motion was over (posture (d)), the robot kept an upright posture while its waist joint get supported by the device. Finally, the robot bent down after we deactivated the device (posture (e-g)). The robot can replicate the entire sequence of up/down motion, as seen from the snapshots. It should be noted that the controller does not know the timing when the human operator activated or deactivated the device. In accordance with the interaction model of the robot device developed by the tracking control, the robot automatically started lifting or putting down.

In the upper ranges of Fig. 6, the result of the torque assessment is shown. In this experiment, we assumed that the assistive torque is equivalent to the desired torque ($\hat{\tau}_{ast}(t = 0) = f_{(x(0))}$) when the observer was initialized ($t = 0$). This assumption is necessary, since the robot already has a weight in front of the device. In actual human use, we can presume that the human beginning is sufficiently supported when the lower back is lifted. This conclusion is thus known as the observer's offset. As a result, the activation timing of the tracking controller was adjusted to a timing when the joint torque in upper row of was zero at about 3.5 s (Fig. 6). The assisted torque can be estimated during the robot reproducing a movement.

While the observer estimates the assistive torque, the tracking controller adjusts x, so that the estimated torque $\hat{\tau}_{ast}$ can track the desired torque $f^{trg}(x)$. The result of adjusting x is shown in the lower row of Fig. 6. From the vector

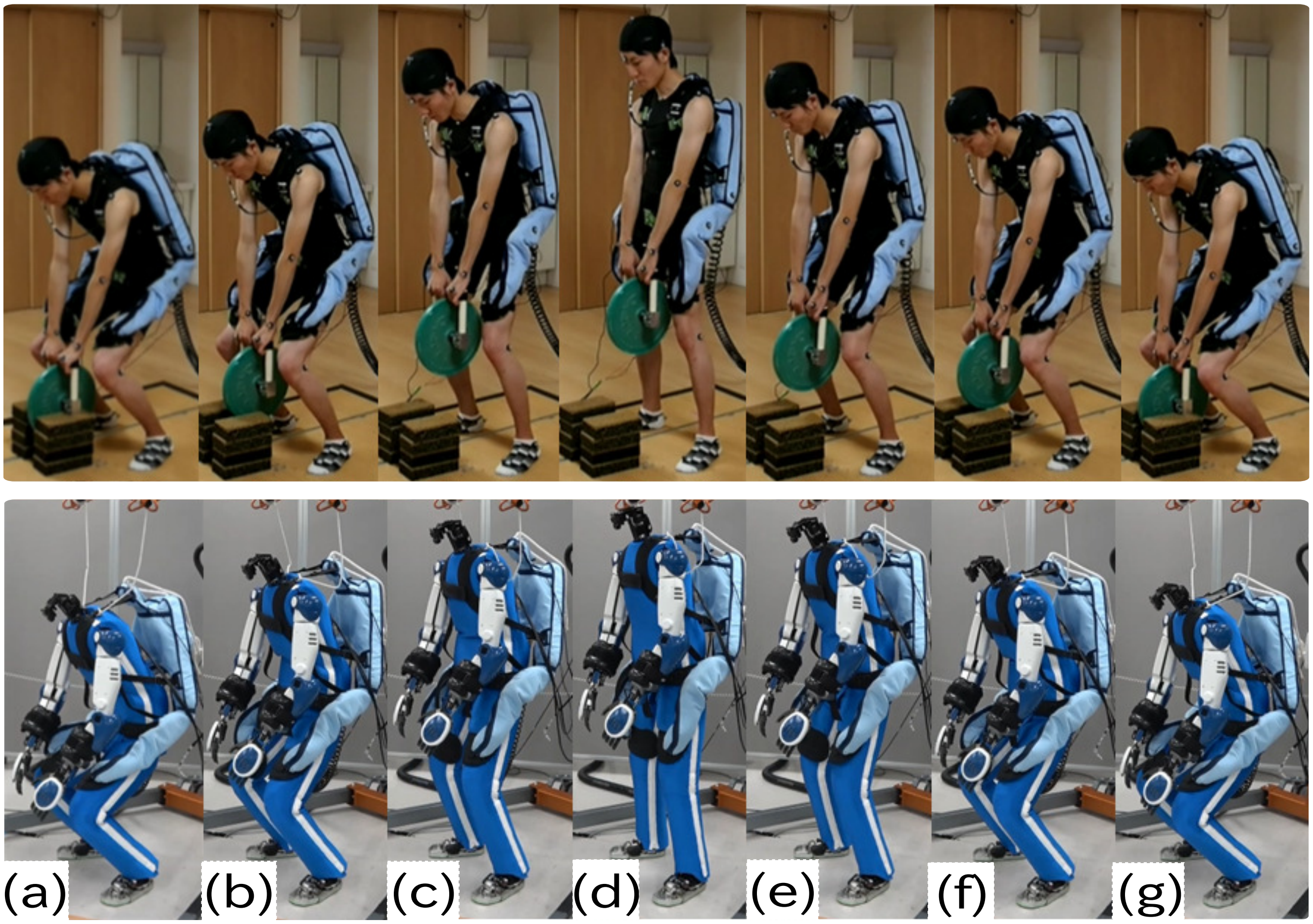

Fig. 5. Result of human motion reproduction by the proposed controller. When the assistive device is activated (starts supporting), the robot starts lift-up motion ((a)-(c)). After achieving an upright posture (d), the robot keeps the posture until the device is deactivated. Finally, the robot put the weight down while the supportive effect decreases ((e)-(g)).

field based tracking controller, $\dot{x}$ as the velocity of x was determined. Then, x gave whole-body joint angles, and the robot reproduced the posture that satisfied $\hat{\tau}_{ast} = f^{trg}_{(x)}$. As a result, $\hat{\tau}_{ast}$ tracks $f^{trg}_{(x)}$ in Fig. 6. Since the robot movement was ended around 17.0 s, the tracking error $f^{trg}_{(x)} - \hat{\tau}_{ast}$ became bigger.

C. Evaluation of Assistive Device

In the previous section, we showed that our controller allows humanoid to reproduce the human motion when wearing the device. In this section, with the proposed controller, we evaluated the assistive device Muscle Suit by the following procedures, similar to those shown in [23]:

1) The humanoid robot wearing the device reproduces a human motion by using the proposed controller. During the motion, we recorded both the joint angles and torques of the robot.
2) The humanoid robot play-back the same motion as that recorded in 1) without the device. The joint torques were recorded during the movement.
3) The motion performed in step 1) and step 2) are same geometric trajectory while the robot uses the device in step 1) but the robot doesn't use it in step 2). By comparing the difference of the torques measured in 1) and 2), the assistive torque of the device during the movement could be extracted quantitatively.

TABLE I
EXPERIMENTAL CONDITION IN STEP 1) AND 2)

	step 1)	step 2)
weight	4kg, 6kg	4kg, 6kg
device	use	not use
measured data	joint angles, torques	joint torques
controller	proposed controller	servo controller

We conducted the evaluation with different weight condition; 4-kg weight and 6-kg weight. The experimental conditions are summarized in Table. I for step 1) and 2) respectively. The joint torque comparison between the motion with the device and without the device are shown in Fig. 7 and 8 for each case of 4-kg and 6-kg, respectively. In both results, the red solid line shows the torque when using the device and the blue line indicates that without the device. The

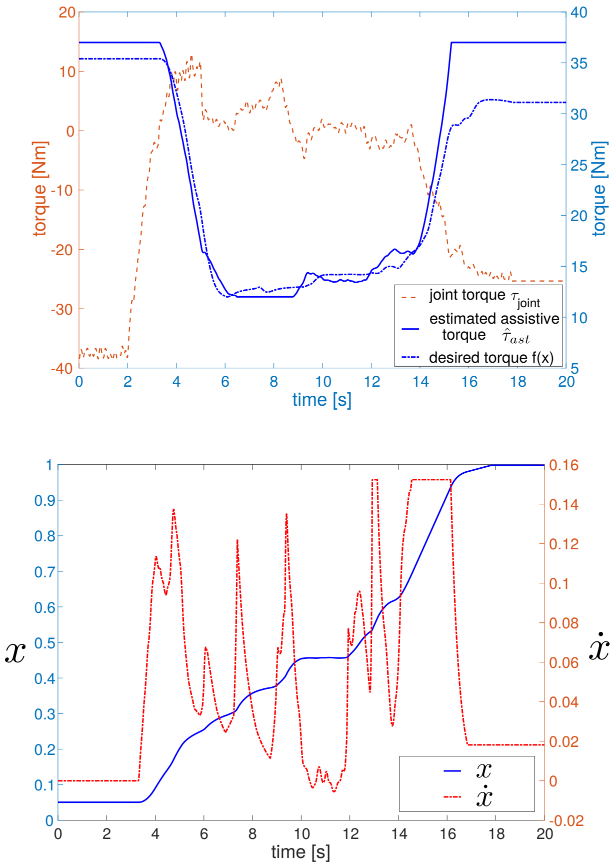

Fig. 6. Result of assistive torque observer (upper row) and tracking controller (lower row).

bending direction generates the positive value of the torque and the straightening direction generates the negative one. In figures, the motion sequences are divided by 3 periods; first period is weight lifting-up motion corresponding to the robot posture depicted in (a) to (c) in Fig. 5, second period is weight keeping motion corresponding to the posture depicted in (d) in Fig. 5, last period is weight putting-down motion corresponding to the posture depicted in (e)-(g) in Fig. 5.

With the 4-kg weight in Fig. 7, the motion continued for about 15 s; the robot lifts a weight in 6-12 s, then keep it with its up straight posture in 12-18 s, and finally puts it down in 18-21 s. That continued for about 17 s with 6-kg weight in Fig. 8. These results show that our controller appropriately adjust x so that the robot can reproduce the motion in the different conditions.

In both results, the torque with the device is decreasing when the robot moves, and converges, which denotes the proposed controller successfully realized the motion with the benefit of assistive torque instead of using the robot joint torque. Without the assistive device, high torque is required to execute the same motion. According to both results, the peak torques (around 65 Nm at 8 s in 4-kg case and around 80 Nm at 5 s in 6-kg case respectively) were efficiently reduced when the robot wearing the device. As seen in both

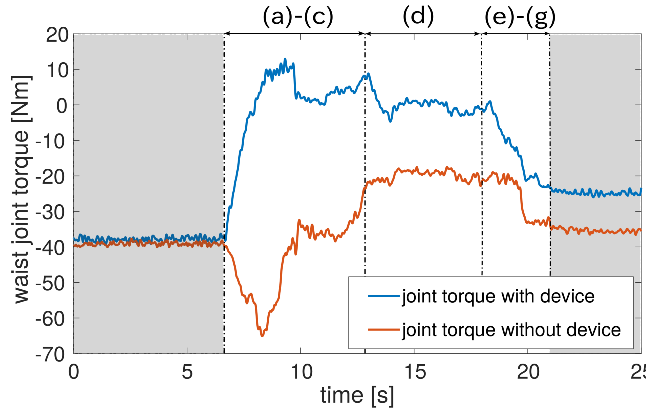

Fig. 7. Torque comparison of the lift-up 4kg weight motion with the device and without device. The motion starts around 6 s when the joint torque changes. The motion continued for 15 s until it ended around 21 s. The motion is divided by 3 periods; first period (6-13 s) is corresponding to motion depicted in (a) to (c) in Fig. 5, second period (13-18 s) is corresponding to motion depicted in (d) in Fig. 5, last period (18-21 s) is corresponding to motion depicted in (e) to (g) in Fig. 5.

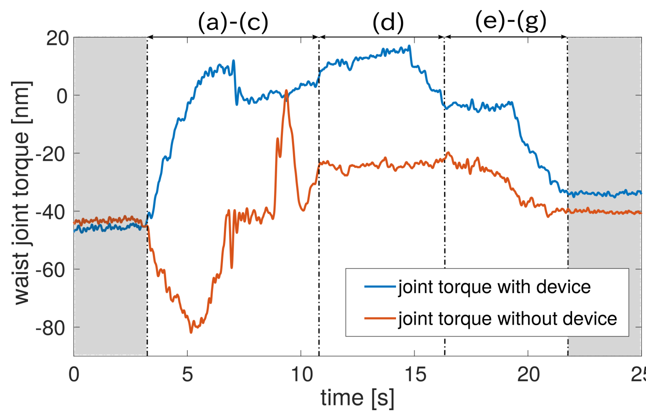

Fig. 8. Torque comparison of the lift-up 6kg weight motion with the device and without device. The motion starts around 4 s when the joint torque start changes. The motion continued for 17 s until it ended around 22 s.

figures, the device reduced the waist joint torque through the overall motion.

Since the Muscle Suit mainly supports the waist joint, we focus on the supportive effect at the waist joint. To confirm the effect of the device at other joints, torque changes of other joints were also compared. The hip joint torque comparison is shown in Fig. 9. Since the device covers the hip joints of the robot, the hip joint gets affected by the supportive effect. The hip joint torque is reduced by using the device in the period when the robot was not moving highlighted by gray in Fig. 9. The torque increases by using the device in the period when the robot is moving. This increase in the hip joint torque was caused by reaction to the reduction of the waist joint torque. However, the increase torque of the hip joint is sufficiently small compared to the decrease torque of the waist joint. The knee joint torque comparison is also shown in Fig. 10. The knee joint does not get affected by the supportive effect because the device is attached to the

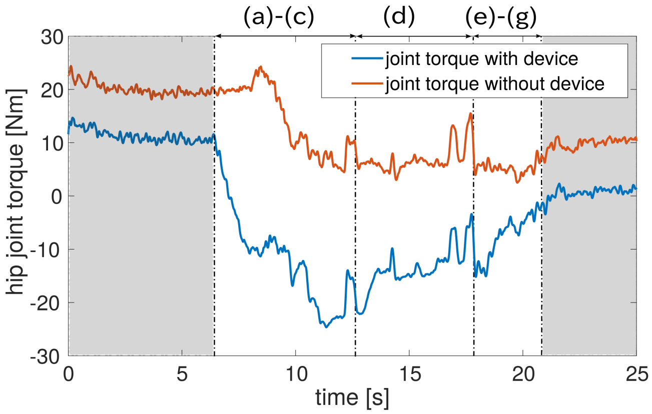

Fig. 9. Hip joint torque comparison of the lift-up 4kg weight motion with the device and without device.

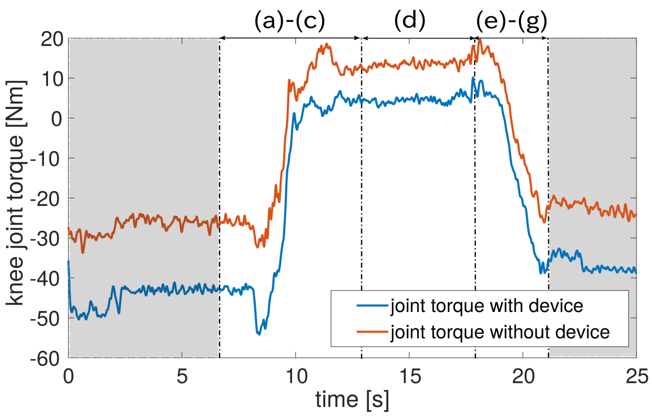

Fig. 10. Knee joint torque comparison of the lift-up 4kg weight motion with the device and without device.

body above the knee, Therefore, the increase in the knee joint torque is due to the increase in weight of the device.

Finally, the assistive effects of the device were extracted by subtracting the torque with the device from that without the device in each case respectively as shown in Fig. 11. The assistive torque with 4-kg weight is approximately 30 Nm on average during the motion and its peak value is 70 Nm which was observed when the robot started lifting up motion. With 6-kg weight, the average torque is around 40 Nm and the peak torque is 85 Nm which was also observed when the robot started motion. From this result, we successfully visualize the assistive effect of the device by using the humanoid.

IV. Conclusions

In this paper, we proposed a control framework for realizing human motion reproduction when wearing the assistive device (exoskeleton) and moving cooperatively with it. The proposed control framework comprises the two different components: (A) the assistive torque observer using the momentum based disturbance observer. (B) The tracking controller based on the vector field designed according to the robot/device interaction model. Combining two components,

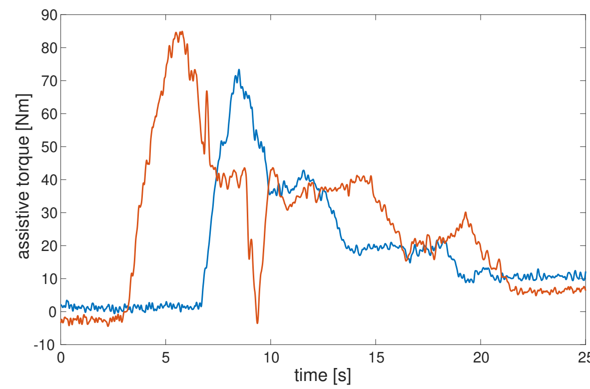

Fig. 11. Result of the assistive torque extraction. The blue line denotes the assistive torque with 4-kg weight and the red one denotes that with 6-kg weight

the robot can imitate the actual usage situation when human muscles are relaxed during the movement when wearing the device. Since our control framework was developed for evaluating the general assistive device, the framework is independent of the device controller so that the robot can achieve the motion reproduction with no modification of the device. Therefore, the robot can wear the device in the same way as humans do and test it. In addition, the proposed framework can evaluate the assistive device by quantifying the assistive effect from the sensor values of the robot.

To validate our control framework, the human motion was recorded by the motion capture system in advance. We recorded the continuous sequence of motion when lifting up and down an object with wearing the device. The recorded motion was used to design the vector field of the controller (B). Then, the proposed control framework was tested by using humanoid HRP-4 wearing the assistive device Muscle Suit. The results of the experiment clearly showed that the robot could move cooperatively while the device assists the waist joint in the same way as humans do. Thanks to the controller (B), we could also generate the continuous sequence of the lifting operation, even though the robot does not know the control state of the assistive device.

The proposed framework could also extract the assistive torque generated by the device during the whole motion sequence. Since extracting the assistive torque of the device is difficult in the human subject experiments, the evaluation using the humanoid robot has a great benefit in providing the performance index to users. The proposed control scheme can perform without the specific model of the device, which shows that we can evaluate the other wearable assistive devices in the same manner.

In this paper, the controller vector field (B) was simply designed from the retargeted human motion. The vector field can represent several characteristics of human motion control. For example, the variance in motion trajectories performing the same tasks depends on how the trajectory in the vector field is pulled in [20], [21]. For more accurate and natural use situations, the advanced design of the vector field is important and will be investigated in the future.

To extend our method towards more complex whole body motions, we need to introduce the vector field that represents the relation between the tracked trajectory and the whole body dynamics including not only waist joint but also other joints. Some researches introduced the path tracking control considering whole body dynamics by using the time parameterization technique [30], [31]. In our framework, the phase parameter in the controller can be designed by using the time parameterization. The integration of such time parameterization techniques is expected to handle the relationship between the trajectory and the whole body dynamics, which will be addressed in our future work.

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