In the field of industrial manufacturing, there are still many parts processed manually. To overcome this problem, a motion-copying system is proposed to make a robot execute the work of a human. However, processing motion data and reproducing new motion data that can be applied to various scenes are required to extend the versatility of the motion-copying system. In this paper, a temporal compensation method is proposed in order to maintain the reproducibility of a saved human motion because loaded human motion data are different from saved human motion data when motion data is processed by spatial scaling. When saved human motion data is processed by spatial scaling, reaction force of saved human motion data and that of loaded human motion data are different, and the reproducibility decreases. Here, temporal compensation, which is based on temporal scaling, is proposed in order to equalize the reaction force of saved human motion data and that of loaded human motion data. Validity was confirmed by the using experiments that save and reproduce writing motion.

**Keywords:** acceleration control, motion-copying system, motion-data processing, temporal compensation

1. Introduction

Recently, Japan becomes aged society with a low birth rate. Because of this phenomenon, successors who take over Japanese skillful technique is decreasing. Hence, Japanese skillful technique is being lost. For this problem, it is thought that we make robots act for and support the human action. In the industrial field, there are the examples that we make robots memorize the human manual operation sequences as the position orbit. Thus robots become indispensable for the human society. However, conventional robots cannot duplicate the human skillful technique because it needs not only position control but also sensitive force control. Hence, real-world haptics is investigated to operate the sensitive force control. As the research about the information of tactile, there is the field of study about the virtual reality that operates the virtual force tactile. However, the aim of real-world haptics is the operation of the real world force tactile that can be obtained from the human hands and so on.

Force tactile is the sense that is different from the visual information or auditory information. Visual and auditory information is the unidirectional information that is representative of the television or radio. On the other hand, force tactile is the bidirectional information that can be obtained when it contacts the environment. Therefore, technology like recording, playing or broadcasting of force tactile can not be established because force tactile is more difficult phenomenon than visual and auditory information to operate. However, in the industrial field or tradition of skillful technique, recording and reproduction of the force tactile of the human motion as with the visual and auditory information are desirable.

Motion capture system is investigated to record and analyze the human motion. The motion capture system is based on the position information of human motion, so it can not apply the subject that affects an environment like writing motion or cutting motion. Then, motion-copying system is suggested as a new technology of recording and reproduction of force tactile. Because the motion-copying system is based on both the position information and the force information, and it can treat the contact motion that is difficult for the motion capture system.

The motion-copying system can save the skillful technique as digital data. Therefore, skillful technique that depend on the experience or the feeling can be analyzed quantitatively. Moreover, it makes improving productivity come true. In addition, skillful technique that is declining can be taken over for the later generations due to apply the motion-copying system to the education system. According to these reasons, the research that can save and reproduce the force tactile as with the visual information is being studied.

In this way, the motion-copying system can make robots reproduce the human motion. But, the present motion-copying system can reproduce only the saved motion. From the above, processing the motion data is important as shown in Fig. 1. However, when the motion data are processed...
spatially, the reproduced reaction force from the environment is different from the saving reaction force from the environment. Then, this paper proposes the temporal compensation method in order to maintain the reproducibility of saved human motion. From this, the motion-copying system can be applied for the various scenes.

This paper is composed of 5 sections. At first, the motion-copying system that is basic technology of this paper is explained in Sect. 2. In addition, the proposed method is described in Sect. 3 and realization approach is in Sect. 4. The validity of the proposed method is confirmed by the experiments in Sect. 5. Conclusion and future works are described in Sect. 6.

2. Motion-Copying System

The motion-copying system is the system that saves the position information and force information of human motion and reproduce the motion by using robots. The motion-copying system consists of the motion-saving system and the motion-loading system. In this section, bilateral control that is the basic technology of the motion-copying system is explained. After that, the motion-saving system and the motion-loading system is explained.

2.1 Bilateral Control

Bilateral control is control method that transfers information bidirectionally between master system that is treated by operator and slave system that works at the environment.

Bilateral control has two goals. One is synchronism of position of master system and slave system. The other is realization of the law of action and reaction between operator’s force and reaction force from environment

\[ x_M - x_S = 0 \]  \hspace{1cm} (1)

\[ F_M + F_s = 0 \]  \hspace{1cm} (2)

where \( x \) denotes position and \( F \) denotes force, and subscript \( M \) and \( S \) mean master system and slave system. Master system and slave system construct the acceleration control system using the disturbance observer (DOB) \(^{10,11}\). A block diagram of the bilateral control system is shown in Fig. 2 where \( C_f \), \( C_p \) denote force regulator and position regulator, respectively. Superscripts \( \text{res} \), \( \text{ref} \), \( \text{ext} \), \( \ast \) mean response, reference, external and estimation, respectively. Subscripts \( C \) and \( D \) denote common mode and differential mode, respectively. External force of master system and slave system is estimated by the reaction force observer (RFOB) \(^{11,12}\). In order to realize the control goal represented as (1) and (2), control variables are transferred from work space on the real-world to virtual space by using the quary matrix \(^{13}\).

\[ Q_2 = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \]  \hspace{1cm} (3)

By using the quary matrix, control variables are transformed to orthogonal common mode space and differential mode space, respectively. Therefore, it is possible for (1) and (2) to construct control system independently. Equation (4) and (5) indicate coordinate transformation to the mode space

\[ \begin{bmatrix} x_C^{\text{ref}} \\ x_D^{\text{ref}} \end{bmatrix} = Q_2 \begin{bmatrix} x_M^{\text{res}} \\ x_S^{\text{res}} \end{bmatrix} \]  \hspace{1cm} (4)

\[ \begin{bmatrix} F_C^{\text{ext}} \\ F_D^{\text{ext}} \end{bmatrix} = Q_2 \begin{bmatrix} F_M^{\text{res}} \\ F_S^{\text{res}} \end{bmatrix} \]  \hspace{1cm} (5)

Equation (1) and (2) can be rewritten as (6) and (7)

\[ x_D^{\text{ref}} = 0 \]  \hspace{1cm} (6)

\[ F_C^{\text{ref}} = 0 \]  \hspace{1cm} (7)

Then, goals of control system is \( F_C^{\text{ext}} = 0 \) and \( x_D^{\text{ref}} = 0 \)

\[ \dot{x}_C^{\text{ref}} = C_f (0 - F_C^{\text{ext}}) \]  \hspace{1cm} (8)

\[ \dot{x}_D^{\text{ref}} = C_p (0 - x_D^{\text{ref}}) \]  \hspace{1cm} (9)

where \( K_f \), \( K_p \), \( K_d \) and \( s \) denote force gain, proportional gain, derivative gain and Laplace operator, respectively. Hence, the acceleration reference of master system \( \ddot{x}_M^{\text{ref}} \) and the slave system \( \ddot{x}_S^{\text{ref}} \) are expressed as

\[ \begin{bmatrix} \ddot{x}_M^{\text{ref}} \\ \ddot{x}_S^{\text{ref}} \end{bmatrix} = Q_2^{-1} \begin{bmatrix} x_C^{\text{ref}} \\ x_D^{\text{ref}} \end{bmatrix} \]  \hspace{1cm} (12)

From this way, bilateral control becomes possible.

2.2 Motion-Saving System

Because basic construction of the motion-saving system is based on the bilateral control, block diagram of the motion-saving system is Fig. 2 that is same as that of bilateral control. This system saves the position and force of master system when the operator manipulates the bilateral system.

2.3 Motion-Loading System

Block diagram of the motion-loading system is Fig. 3. Basic construction of the motion-loading system is based on the bilateral control as.

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**Fig. 2.** Block diagram of bilateral control system

**Fig. 3.** Block diagram of the motion-loading system
with the motion-saving system. The motion-loading system consists of the slave system only because motion data memory that the position and force of master system are recorded becomes virtual master system. From the above, the saved human motion can be reproduced by using the virtual master system and slave system.

3. Design of Temporal Scaling for The Spatial Scaling

High reproducibility as for the motion-copying system is that both position and reaction force will match when human motion is saved and loaded. If the work environment does not change, reaction force is same between saving phase and loading phase. But, when human motion data are processed by spatial scaling, reaction force of loaded motion is different from that of saved motion. So, reproducibility of human motion fails. This is because human motion data are processed by spatial scaling at same time width, and motion speed and motion acceleration are changed. Reaction force of saved motion indicates (13) and reaction force of loaded motion with a times spatial scaling indicates (14)

\[
F_{\text{ext}}^a(t) = M\ddot{x}^{res}(t) + KD\dot{x}^{res}(t) + Kx^{res}(t) \quad \cdots \cdots \quad (13)
\]

\[
F_{\text{ld}}^a(t) = aM\ddot{x}^{res}(t) + aKD\dot{x}^{res}(t) + aKx^{res}(t) \quad \cdots \cdots \quad (14)
\]

where \(M\), \(D\) and \(K\) denote the mass, coefficient of viscosity and coefficient of elasticity, respectively. Equations (13) and (14) reveal that reaction force of loaded motion is different from that of saved motion. In this paper, a method that makes different reaction force equalize is proposed by using the temporal compensation that is based on the temporal scaling.

Here, reaction force of loaded motion with a times spatial scaling and b times temporal scaling can be represented as

\[
F_{\text{ext}}^{ab}(t) = \frac{a}{b^2}M\ddot{x}^{res}(t) + \frac{a}{b}KD\dot{x}^{res}(t) + aKx^{res}(t)
\]

\[= \left(1 - \frac{a}{b^2}\right)M\ddot{x}^{res}(t) + \left(1 - \frac{a}{b}\right)KD\dot{x}^{res}(t) + (1 - a)Kx^{res}(t) = 0 \quad \cdots \cdots \quad (15)
\]

If temporal scaling \(b\) is applied, total time of the motion has changed. Therefore, processed motion data need to be normalized in order to compare to the original data. In other words, if \(e^{\text{ext}}(t)\) satisfies (16), reaction force of loaded motion becomes equal reaction force of saved motion and reproducibility is maintained. Where, \(e^{\text{ext}}(t)\) is errors between \(F_{\text{ext}}^a(t)\) and \(F_{\text{ld}}^a(bt)\) (or \(F_{\text{ext}}^a(t/b)\) and \(F_{\text{ld}}^a(t)\))

\[
e^{\text{ext}}(t) = F_{\text{ext}}^a(t) - F_{\text{ld}}^a(bt)
\]

\[= \left(1 - \frac{a}{b^2}\right)M\ddot{x}^{res}(t) + \left(1 - \frac{a}{b}\right)KD\dot{x}^{res}(t) + (1 - a)Kx^{res}(t) = 0 \quad \cdots \cdots \quad (16)
\]

where \((1 - a)Kx^{res}(t)\) is independent of temporal scaling \(b\), and it is too small in the environment considering in this article. The temporal scaling \(b\) should be satisfied with (17)

\[
e^{\text{ext}}(t) = \left(1 - \frac{a}{b^2}\right)M\ddot{x}^{res}(t) + \left(1 - \frac{a}{b}\right)KD\dot{x}^{res}(t) + (1 - a)Kx^{res}(t)
\]

\[= \left(1 - \frac{a}{b^2}\right)M\ddot{x}^{res}(t) + \left(1 - \frac{a}{b}\right)KD\dot{x}^{res}(t) = 0 \quad \cdots \cdots \quad (17)
\]

By using formula of the solution of the quadratic equation about (17), temporal scaling \(b\) is obtained as

\[
b(t) = \frac{ap \pm \sqrt{a^2p^2 + 4aq(p + q)}}{2(p + q)} \quad \cdots \cdots \quad (18)
\]

where \(p\) and \(q\) indicate \(D\ddot{x}^{res}(t)\) and \(M\ddot{x}^{res}(t)\), respectively. Here, it is clear that temporal scaling \(b\) is time varying from (18). In this paper, when replay speed of motion is altered, saved motion data are developed by Fourier series and approximated as continuous function in order to solve the disagreement between sampling time of motion data and control period. So, if temporal scaling \(b\) is time varying, control performance is down by the much computational complexity. Then, by thinking of \(M\ddot{x}^{res}(t)\) and \(D\ddot{x}^{res}(t)\) that are the average value of \(M\ddot{x}^{res}(t)\) and \(D\ddot{x}^{res}(t)\), temporal scaling \(b\) can be regarded as constant. Then the relationship between the ratio of \(D\ddot{x}^{res}(t)\) and \(M\ddot{x}^{res}(t)\) for the reaction force \(F_{\text{ld}}^a(t)\) is regarded as \(\alpha \) and \(1 - \alpha\), respectively

\[
\frac{M\ddot{x}^{res}(t)}{D\ddot{x}^{res}(t)} = 1 - \alpha : \alpha \quad \cdots \cdots \quad (19)
\]

The relationship between \(M\ddot{x}^{res}(t)\) and \(D\ddot{x}^{res}(t)\) can be written as (20) from (19)

\[
D\ddot{x}^{res}(t) = \frac{\alpha}{1 - \alpha}M\ddot{x}^{res}(t) \quad \cdots \cdots \quad (20)
\]

\(\alpha\) can be obtained by identifying saved motion data. Equation (21) can be obtained by substituting (20) for (18)

\[b = \frac{aa + \sqrt{a^2a^2 + 4(1 - a)a}}{2} \quad \cdots \cdots \quad (21)
\]

where temporal scaling \(b\) can be represented as (22) considering \(a > 0, b > 0\) and \(0 < \alpha < 1\).

\[b = \frac{aa + \sqrt{a^2a^2 + 4(1 - a)a}}{2} \quad \cdots \cdots \quad (22)
\]

From the above, temporal scaling \(b\) can be obtained.

4. Realization Approach of Temporal Scaling

Mass, viscosity coefficient and elasticity coefficient need to be identified in order to obtain temporal scaling \(b\). So, in this paper, each coefficient is identified by least squares method. And, saved motion data are developed by Fourier series and approximated as continuous function in order to solve the disagreement between sampling time of motion data and control period.

4.1 Identification of Environment Model by Least Squares Method

An estimated reaction force \(\hat{F}_{\text{ext}}^a\) can be written as (23) by using the saved human motion data

\[
\hat{F}_{\text{ext}}^a = \hat{M}\ddot{x}^{res}(t) + \hat{D}\dot{x}^{res}(t) + \hat{K}x^{res}(t) \quad \cdots \cdots \quad (23)
\]

When human motion data are saved in \(t_s \leq t \leq t_e\), \(\hat{M}, \hat{D}\) and \(\hat{K}\) that integral square errors of reaction force of saved motion \(F_{\text{ext}}^a\) and estimated reaction force \(\hat{F}_{\text{ext}}^a\) become equal is considered

\[
S_e = \int_{t_s}^{t_e} (F_{\text{ext}}^a - \hat{F}_{\text{ext}}^a)^2 dt = 0 \quad \cdots \cdots \quad (24)
\]

When partial differentiation of \(\hat{M}, \hat{D}\) and \(\hat{K}\) about (24) are considered, (25) to (27) are obtained
\[
\frac{\partial S_c}{\partial M} = \int_{t_i}^{t_e} (-2F_{sw}^{ext}\dot{x}^{res}(t) + 2\dot{M}\ddot{x}^{res}(t)) dt + 2\dot{D}\dot{x}^{res}(t)\dot{x}^{res}(t) + 2\dot{K}\ddot{x}^{res}(t)\dot{x}^{res}(t)) dt = 0 \quad \cdots (25)
\]
\[
\frac{\partial S_c}{\partial D} = \int_{t_i}^{t_e} (-2F_{sw}^{ext}\dot{x}^{res}(t) + 2\dot{D}\dot{x}^{res}(t)) dt + 2\dot{K}\ddot{x}^{res}(t)\dot{x}^{res}(t) + 2\dot{M}\dot{x}^{res}(t)\dot{x}^{res}(t)) dt = 0 \quad \cdots (26)
\]
\[
\frac{\partial S_c}{\partial k} = \int_{t_i}^{t_e} (-2F_{sw}^{ext}\dot{x}^{res}(t) + 2\dot{M}\ddot{x}^{res}(t) + 2\dot{M}\ddot{x}^{res}(t)) dt + 2\dot{D}\dot{x}^{res}(t)\dot{x}^{res}(t)) dt = 0 \quad \cdots (27)
\]

Here, (25), (26) and (27) are depicted as matrix form, these equations are rewritten as

\[
\begin{bmatrix}
  a_{11} & a_{12} & a_{13} \\
  a_{21} & a_{22} & a_{23} \\
  a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
  \hat{M} \\
  \hat{D} \\
  \hat{K}
\end{bmatrix}
= \int_{t_i}^{t_e} F_{sw}^{ext}\dot{x}^{res}(t) dt \quad \cdots (28)
\]

where each coefficients are

\[
a_{11} = \int_{t_i}^{t_e} \dddot{x}^{res}(t)^2 dt;
\]
\[
a_{22} = \int_{t_i}^{t_e} \dddot{x}^{res}(t)^2 dt;
\]
\[
a_{33} = \int_{t_i}^{t_e} \dddot{x}^{res}(t)^2 dt;
\]
\[
a_{12} = a_{21} = \int_{t_i}^{t_e} \dddot{x}^{res}(t)\dddot{x}^{res}(t) dt;
\]
\[
a_{13} = a_{31} = \int_{t_i}^{t_e} \dddot{x}^{res}(t)\dddot{x}^{res}(t) dt;
\]
\[
a_{23} = a_{32} = \int_{t_i}^{t_e} \dddot{x}^{res}(t)\dddot{x}^{res}(t) dt.
\]

From the above, \( \hat{M}, \hat{D} \) and \( \hat{K} \) are obtained from (28).

### 4.2 Resampling of Human Motion Data by Fourier Series

There is the problem that sampling time of motion data and control period disagree because saved human motion data are discrete data. Then, it is thought that saved human motion data are transformed into the continuous function that is described as the sum of sine wave and cosine wave by using the Fourier series and are resampled in accordance with the temporal scaling and control period. If saved human motion data, that data number is \( N \), is considered as \( f(n) \), the Fourier transform of this can be described as

\[
F(k) = \sum_{n=0}^{N-1} f(n) \exp\left(-\frac{j2\pi kn}{N}\right) \quad \cdots (29)
\]

where \( j \) is the imaginary unit and \( k \) indicates natural numbers \( 0 \) to \( N - 1 \). A new human motion data that consider the temporal scaling \( b \) is obtained by the inverse transform of (29), and it can be described as

\[
f_b(n) = \frac{1}{N} \sum_{k=0}^{N-1} F(k) \exp\left(-\frac{j2\pi kn}{N}\right) \quad \cdots (30)
\]

where \( n \) indicates natural numbers \( 0 \) to \( (N - 1)/b \). By using the new motion data that are obtained from (30), motion that considers the temporal scaling \( b \) can be reproduced.

### 5. Experiments

In this section, a verification experiment to confirm the validity of proposed method is conducted. In this experiment, the robot that has three degree of freedom is used in order to save, process and reproduce the human motion.

#### 5.1 Experimental Setup

The experimental setup is shown as Fig. 4. The robot has the system that has two rotary motors and linear motor. This system is used to both master system and slave system. Two rotary motors have the degree of freedom of \( x - y \) plane and linear motor has that of \( z \) axis. A writing material is attached to the linear motor of slave system, and operator handles the master system. Then, parameters of experimental system are shown as Table 1.

![Fig. 4. Experimental system](image)

<table>
<thead>
<tr>
<th>Description</th>
<th>Rotary motor</th>
<th>Linear motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_s )</td>
<td>Sampling time</td>
<td>0.1 ms</td>
</tr>
<tr>
<td>( K_m )</td>
<td>Nominal torque coefficient</td>
<td>1.18 Nm/A</td>
</tr>
<tr>
<td>( K_p )</td>
<td>Position gain</td>
<td>2500</td>
</tr>
<tr>
<td>( K_v )</td>
<td>Velocity gain</td>
<td>700</td>
</tr>
<tr>
<td>( K_f )</td>
<td>Force gain</td>
<td>25</td>
</tr>
<tr>
<td>( g_{sw} )</td>
<td>Cut-off frequency of DOB</td>
<td>100 rad/s</td>
</tr>
<tr>
<td>( g_{sw} )</td>
<td>Cut-off frequency of RFOB</td>
<td>100 rad/s</td>
</tr>
<tr>
<td>( M )</td>
<td>Nominal mass</td>
<td>0.0038 kgm^2</td>
</tr>
<tr>
<td>( l )</td>
<td>Link length</td>
<td>0.32 m</td>
</tr>
<tr>
<td>( D )</td>
<td>Coefficient of viscosity</td>
<td>–</td>
</tr>
<tr>
<td>( M )</td>
<td>Mass</td>
<td>–</td>
</tr>
</tbody>
</table>

By using the robot, the human motion of the writing is saved by the the motion-saving system. The data, that is saved, are the position and force responses of rotary motor 1, 2 and linear motor. In this experiment, human motion data is processed with two times spatial scaling about both \( x \) axis and \( y \) axis. \( M, \dot{D} \) and \( \dot{K} \) are identified and \( \alpha \) is obtained in order to calculate the temporal scaling \( b \) that corresponds to the spatial scaling \( a \). And in this experiment, the result of the position and force responses using the temporal compensation and using no compensation are compared.
5.2 Experimental Results

By the identification of environmental model, \( \alpha = 0.8959 \) and \( b = 1.9013 \) are obtained. The experimental results are shown as from Fig. 5 to Fig. 24. In Figs. 10, 12, 19, 20, 23, 24, processed motion are normalized to compare the conventional and proposed method. Where, \( x_{s}^{\text{res}}(t) \) and \( y_{s}^{\text{res}}(t) \) indicate x and y position responses of saved human motion, and \( x_{ld}^{\text{ori}}(t) \) and \( y_{ld}^{\text{ori}}(t) \) are x and y position responses of loaded original motion, and \( x_{ld}^{\text{res}}(t) \) and \( y_{ld}^{\text{res}}(t) \) indicate x and y position responses of loaded human motion that processed by spatial scaling \( a \) and temporal scaling \( b \). Similarly, \( F_{s}^{\text{ext}}(t) \) and \( F_{s}^{\text{int}}(t) \) indicate force responses of rotary motor 1 and 2 of saved human motion, and \( F_{ld}^{\text{ori}}(t) \) and \( F_{ld}^{\text{ori}}(t) \) are force responses of rotary motor 1 and 2 of loaded original motion, and \( F_{ld}^{\text{res}}(t) \) and \( F_{ld}^{\text{res}}(t) \) indicate force responses of loaded human motion that processed by spatial scaling \( a \) and temporal scaling \( b \).

Figure 5 to Fig. 8 represent x and y position responses and those errors. In the same way, Fig. 13 to Fig. 16 represent force responses of rotary motor 1 and 2. These are just the motion loading results that are not processed and it can be find that motion saving and loading are achieved. Then, Two times spatial scaling about \( x \) axis is achieved from Figs. 9 and 10 because the errors in Fig. 10 are very small. Similarly, two times spatial scaling about \( y \) axis is achieved from Figs. 11 and 12. And, errors of force responses with and without temporal compensation about rotary motor 1 diminish from Fig. 17 to Fig. 20. Similarly, errors of force responses with and without temporal compensation about rotary motor 2 diminish from Fig. 21 to Fig. 24. Then, Table 2 indicates the root mean square errors between saved human motion data and loaded human motion data of rotary motor. From this, the root mean square errors with temporal compensation is less than that without temporal compensation. So, reaction force from environment can be reproduced more accurately.
Motion-Data Processing and Reproduction Based on Motion-Copying System (Ko Igarashi et al.)

Fig. 13. Torque responses of rotary motor 1 of original data $F_{ext}^{ori}(t)$ and loaded data $F_{ext}^{ldorr}(t)$

Fig. 14. Error of torque responses of rotary motor 1 of $F_{ext}^{ori}(t)$ and $F_{ext}^{ldorr}(t)$

Fig. 15. Torque responses of rotary motor 1 of original data $F_{ext}^{ori}(t)$ and loaded data $F_{ext}^{ldorr}(t)$

Fig. 16. Error of torque responses of rotary motor 1 of $F_{ext}^{ori}(t)$ and $F_{ext}^{ldorr}(t)$

Fig. 17. Torque responses of rotary motor 1 of original data $F_{ext}^{ori}(t)$ and processed data $F_{ext}^{ld}(t)$

Fig. 18. Error of torque responses of rotary motor 1 of $F_{ext}^{ori}(t)$ and $F_{ext}^{ld}(t)$

Fig. 19. Torque responses of rotary motor 1 of original data $F_{ext}^{ori}(t)$ and loaded data $F_{ext}^{ld}(t)$

Fig. 20. Error of torque responses of rotary motor 1 of $F_{ext}^{ori}(t)$ and $F_{ext}^{ld}(t)$

Fig. 21. Torque responses of rotary motor 2 of original data $F_{ext}^{ori}(t)$ and processed data $F_{ext}^{ld}(t)$

Fig. 22. Error of torque responses of rotary motor 2 of $F_{ext}^{ori}(t)$ and $F_{ext}^{ld}(t)$

Fig. 23. Torque responses of rotary motor 2 of original data $F_{ext}^{ori}(t)$ and processed data $F_{ext}^{ld}(t)$

Fig. 24. Error of torque responses of rotary motor 2 of $F_{ext}^{ori}(t)$ and $F_{ext}^{ld}(t)$

Table 2. Root mean square of errors of torque responses with and without spatiotemporal compensation

<table>
<thead>
<tr>
<th>Without compensation [Nm]</th>
<th>With compensation [Nm]</th>
<th>Loaded original motion data [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary motor 1</td>
<td>0.6469</td>
<td>0.2796</td>
</tr>
<tr>
<td>Rotary motor 2</td>
<td>0.8460</td>
<td>0.3456</td>
</tr>
</tbody>
</table>

6. Conclusions

In this paper, the temporal compensation method is proposed in order to maintain the reproducibility of saving...
human motion because loaded human motion data are different from saved human motion data when motion data are processed by spatial scaling. In Sect. 2, the motion-copying system that is basic technology of reproduction of human motion is described. In Sects. 3 and 4, the proposed method in this paper that is the temporal scaling for the spatial scaling is described. When saved human motion data are processed by spatial scaling, reaction force of saved human motion data and that of loaded human motion data are different, and the reproducibility decreases. Here, the temporal compensation that is based on the temporal scaling is proposed in order to equalize reaction force of saved human motion data and that of loaded human motion data. In Sect. 5, an experiment is carried out to confirm the proposed method. By using the temporal compensation for spatial scaling, errors of reaction force of saved human motion data and that of loaded human motion data reduced.

By using this method to saved motion data, human motion processing and reproduction of high reproducibility becomes possible. From the above, versatility of the motion-copying system is expanded.

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