Path restriction and speed regulation via force feedback-type welding teaching device using magnetorheological brakes

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Abstract

Welding is one of the forms of nonautomated, heavy labor used in the shipbuilding industry. In the shipbuilding process, the hull is first welded by an industrial automatic welding machine, then irregular welded part correction and welding in narrow places that machines cannot reach are performed by welding workers. Welding operators are required to weld indeterminate objects in narrow working spaces. In addition, it is difficult to perform high-quality welding because the ability to accurately trace a welding line at a constant speed requires a long training period. In this research, a welding training device that assists trainees in skill acquisition was developed. The proposed device, which comprises two magnetorheological (MR) brakes, renders a welding path and restricts welding speed. The MR brakes have a response speed comparable to that of powder brakes, have a high output-to-weight ratio, and are also considered to be suitable for use in welding training devices. A prototype and control strategy were developed, and the performance of the device in actual welding work was evaluated. Results show that path rendering strategy is possible to present routes with an accuracy of 1 mm or better and speed control strategy can regulate the speed required for welding.

Keywords: force feedback device, magnetorheological fluid, welding, teaching device

(Some figures may appear in colour only in the online journal)

1. Introduction

Some countries, such as Japan and China, are experiencing declining birthrates and aging of the population, which together lead to a decrease in the working population [1, 2]. Shipbuilding sites are no exception, with a shortage of skilled workers and a shortage of welding instructors [3]. In the shipbuilding industry [4], the hull is first welded by an industrial automatic welding machine. Then, irregular welded part correction and welding in narrow places that machines cannot reach are performed by welding workers. If irregular welding occurs, the strength of the members decreases and the defect rate increases. Therefore, welding workers are necessary to move welding torches along appropriate paths and at appropriate speeds [5]. However, in shipbuilding, the work is irregular, depending on the welding point, and spaces are narrow; hence, it is difficult to perform high-quality welding accurately, and welding workers must be highly skilled. For these reasons, training in manual welding is indispensable in the shipbuilding industry. However, training welders typically requires a long period of time [6, 7]—approximately more than 3 years. Therefore, in this study, we focused on developing a training device for welding.

In a previous study on motion teaching, a system was developed that differentiates between learners and skilled
workers using visual information obtained with head-mounted displays [8–10]. In this method, since the only information used for teaching is images from head-mounted displays, the cost is low. However, this method is not suitable for use in teaching welding because the light generated during welding is so strong that the trainee cannot see the position of the torch clearly. A motion teaching device using a motor for learning calligraphy has also been developed [11, 12]. This type of device can produce force sensations when a welding torch is moved, but active force rendering may be dangerous to the operator if a malfunction occurs because welding uses high-voltage electricity. It is therefore desirable to develop a welding teaching device that is passive. Haptic presentation using passive elements requires high response speeds and backdrivability, because welding requires an accuracy of 1 mm or higher [13] and thus a high response speed. In terms of backdrivability, the drag resistance and inertia must be small because the device must operate in response to the force applied by the operator. A device using electrorheological (ER) fluid has been developed as a passive force rendering device [14, 15]. This device has succeeded in rendering force sensations utilizing the quick response of the ER fluid brake. However, a characteristic of ER fluid is that it is highly sensitive to heat [16, 17]. As a result, when an ER brake is used in the welding field, the brake characteristics may be adversely affected by welding temperatures and may not operate properly. This study was focused on the use of magnetorheological (MR) fluid brakes. MR fluid is less sensitive to heat than ER fluid [18], and MR brakes have higher torque-to-weight ratios than ER brakes [19].

In this research, a force rendering method using MR brakes for teaching welding was proposed. The proposed method is expected to be able to safely teach the path and speed of welding in a practical environment. In this paper, the path and velocity restriction strategy is proposed and tested in a two-dimensional plane as an initial step toward the development of a training device. The remainder of this paper is organized as follows. First, a concept and prototype for a welding teaching device using MR brakes is proposed. Next, the development and testing of a path and velocity rendering strategy is presented. Finally, the effectiveness of the proposed method is demonstrated using the results of actual welding experiments. The parameters and variables used in this study are listed in table A1 in appendix A.

2. Welding teaching device using MR brakes

2.1. Concept

Figure 1 illustrates the concept of the teaching device. The device is fixed to the welding surface by magnetic force, and the root joint closest to the fixed part is driven by the MR brake. The fixing part to the welding surface and the torch fixing part are connected via an arm. The process for using the device is as follows.

- The device is fixed to the welding surface.
- A desirable welding path and velocity are set.

Figure 1. Concept of welding teaching device. The device is attached to the welding board, and the operator moves a torch along the route presented by the device.

### Table 1. Specification of the prototype.

| Weight [kg] | 2.56 |
| Resolution of rotary encoder [P/R] | 1500 |
| Maximum torque [Nm] | 4 |

### Table 2. Length of each arm of the prototype. Parameters are indicated in figure 4.

| l0 [m] | 0.076 |
| l1 [m] | 0.325 |
| l2 [m] | 0.374 |
| l3 [m] | 0.391 |
| l4 [m] | 0.388 |
| l5 [m] | 0.071 |

- Welding is performed while path and speed correction information are received.

This makes it possible to apply the device to a wide variety of welding targets. The device is safe because it is driven by a passive element, the MR brake.

2.2. Prototype

Figure 2 illustrates the structure of the prototype, table 1 lists its specifications, and table 2 shows length of each links. The prototype consists of a five-bar linkage with two rotary encoders (OMRON Corporation, E6B2-CWZ5C [20]) coaxial with the MR brake (Fuji Latex, FMR-70 S-403 [21]) at the base. The response of the brake torque to the input voltage of the MR brake can be approximated to first order time-delay system which has about 40 ms time constant. To prevent the arm from bending, ball rollers are attached to links and support it. The length of the links were determined experimentally to enable welding of 200 mm line since most of the welding length in the field is less than 200 mm.

Figure 3 presents the operating environment. The device is placed on a workbench, and the base MR brake is connected to the MR driver. The root encoder is connected to Pass-Box 2.
3. Path rendering strategy

3.1. Calculation of the position of end effector

The geometric model of the prototype is illustrated in figure 4. Let each pair of links be $P_i$, let each coordinate be $(x, y)$, and let the link length be $l_i$. Take the center point of $P_1 P_2$ as the origin, and determine its coordinates. The values of $L$, $\alpha$, and $\beta$ are determined as shown in figure 5. The position of the end effector $(x, y)$ can be expressed as follows, based on the kinematic relation:

$$ x = \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x_4 + (l_4 + l_5) \cos (\alpha + \beta) \\ x_4 + (l_4 + l_5) \sin (\beta + \alpha) \end{bmatrix}. $$

(1)

Note that $L$, $\alpha$, $\beta$, $x_3$, $y_3$, $x_4$, and $y_4$ are expressed as follows:

$$ L = \sqrt{(y_3 - y_4)^2 + (x_3 - x_4)^2}, $$

(2)

$$ \beta = \tan^{-1} \left( \frac{y_3 - y_4}{x_3 - x_4} \right), $$

(3)

$$ x_3 = \frac{L}{2} + l_1 \cos \theta_1, $$

(5)

$$ y_3 = l_1 \sin \theta_1, $$

(6)

$$ x_4 = -\frac{L}{2} + l_2 \cos \theta_2, $$

(7)

$$ y_4 = l_2 \sin \theta_2, $$

(8)

3.2. Path rendering

Considering route correction using the MR brake, activating the two MR brakes when the end effector is beyond the welding line completely restricts the movement of the end effector. Therefore, smooth route correction is performed by operating only one MR brake according to the route. Figure 6 presents a schematic diagram of the correction method.

First, let the ideal welding line be the reference line $y = y_0$, and set the limit lines $y = y_0 + \Delta y$ and $y = y_0 - \Delta y$ to sandwich the ideal welding line from above and below. When the hand lies between the limit lines, as in (1), the two MR brakes are not activated, and the hand can move freely. When the hand moves beyond the limit line, as in (2) and (3), only one MR brake is activated. For example, if the vehicle deviates upward...
\( \alpha \) is the angle between \( P_3P_4 \) and \( P_4P_5 \). \( \beta \) is the angle between \( P_3P_4 \) and the horizontal.

![Diagram showing angles and coordinates](image)

**Figure 5.** \( \alpha \) is the angle between \( P_3P_4 \) and \( P_4P_5 \). \( \beta \) is the angle between \( P_3P_4 \) and the horizontal.

**Figure 6.** Smooth route presented by operating a single MR brake according to the route. First, the ideal welding line is set to the reference line \( y = y_0 \), and the limit line is set to \( y = y_0 + \Delta y \) to ensure that the ideal welding line is sandwiched from above and below. Thereafter, \( y \) is set to \( y = y_0 - \Delta y \). When the end effector is located between the limit lines, as in (1), the two MR brakes do not operate. When the end effector is located beyond the limit line, as in (2) and (3), only one MR brake is activated.

(2), Brake 1 on the left is turned on. Thereafter, the motion of the end effector is constrained by a circular motion with one degree of freedom (DOF); thus, it moves downward in response to the force of the operator and attempts to return to the path. Similarly, when the vehicle deviates downward, if only the right MR brake is driven, the hand returns to the path.

**3.3. Path rendering experiment**

We conducted a path rendering experiment using the path rendering strategy. The device shown in figure 2 and the experimental setup shown in figure 3 were used for the experiment. In the experiment, the reference lines parallel to the \( x \)-axis were set to \( y_0 = 550 \) mm and \( \Delta y = \pm 0.5 \) mm, and the end effector was operated to follow the path from left to right. The purpose of this experiment was to confirm the path rendering strategy; hence, a welding torch was not attached to the hand. In both with and without rendering conditions, the prototype was used, and MR brakes are activated only with path rendering condition. Without path rendering, the operator moved the end effector to follow the line previously drawn at \( y = 550 \) mm. With path rendering, the MR brake was operated at 0 Nm when OFF and 4 Nm when ON. During the experiment, a camera was not used for measurement of the position of the end effector, and the position of the end effector calculated using the rotary encoder was measured.

**Figure 7.** Results of position control experiment: displacement of position coordinates with and without control at \( y_0 = 550 \) mm.

![Graph showing position control experiment results](image)

**Figure 7.** Results of position control experiment: displacement of position coordinates with and without control at \( y_0 = 550 \) mm.

4. **Velocity restriction strategy**

4.1. **Strategy**

This section describes the hand speed restriction method. Feedback control is the most commonly used strategy for speed control. Speed restriction via feedback control is described as follows. In feedback control, the detected value is compared with the target value, and the deviation is utilized to calculate the input value to the system. In the case of the prototyped welding teaching device, the target speed is compared with the speed of the end effector calculated by differentiating the position of the end effector. However, this method is effective only when the sensor has sufficient resolution. If its resolution is insufficient, and the minimum speed that can be detected by the end effector is less than the target speed, the speed restriction strategy does not function appropriately. For this device, it is necessary to maintain the welding path...
at an extremely low speed of 3 mm s\(^{-1}\), although a path several hundred millimeters in length needs to be rendered. This is infeasible because, when the device is controlled at 1 kHz, a position accuracy of at least 0.003 mm is required.

Therefore, we propose a speed restriction method that employs a virtual moving wall (figure 8). First, a straight line \(x = kt\) (where \(k\) is a constant, and \(t\) is the time [s]) is set perpendicular to the welding path \(y = y_0\). When the position of the end effector exceeds \(x\), the MR brakes are activated, and a braking force is applied to the end effector. Thereafter, a virtual wall that moves at a constant speed along the direction of the hand is provided. The restriction is performed by this virtual wall. Using this method, the resolution problem can be addressed. Moreover, using a control strategy implemented in Matlab/Simulink, two MR brakes are activated when the end effector is within the virtual wall; however, they are not activated when the end effector is beyond the wall.

4.2. Velocity restriction experiment

This section describes how velocity restriction based on the proposed speed control strategy was tested. The experimental equipment shown in figure 2 was used for the experiment. Here, when the velocity is calculated with the rotary encoder, the device has, the velocity is calculated by differentiating the position of the end effector. However, since the encoder outputs pulses, discontinuity appears when the position is differentiated at very slow motion of 3 mm s\(^{-1}\). Therefore, the velocity of the end effector was measured using the camera.

For comparison, the feedback strategy was evaluated under the same conditions. The command value of the velocity was 3 mm s\(^{-1}\). For the hand route, a straight line with \(y_0 = 550\) was set in the range of \(40 \leq x \leq 400\). A line was drawn on the measurement path, the velocity was restricted by two velocity restriction methods, and the velocity was measured with a high-speed microscope. It should be noted that the velocity measured using the encoder was not used because its resolution was insufficient for accurately measuring the velocity. The proportional–integral–derivative control strategy shown in figure 9 was used as the feedback strategy. The braking torque calculation procedure is described in the appendix of this paper.

Figure 10 illustrates the experimental results. The results show that, in the case of feedback control, the speed was uneven and deviated significantly from the target value of 3 mm s\(^{-1}\). In contrast, in the case of the proposed method, the accuracy was considerably improved, and the speed was almost equal to the target speed. This confirms the effectiveness of the speed control strategy used with the proposed method.

5. Welding experiment

5.1. Objective

As a first step in developing the welding teaching device, a welding experiment was conducted to determine whether welding with less unevenness was possible by means of pass regulation and velocity restriction strategy using the prototype.

5.2. Experimental set up and condition

Figure 11 shows the experimental setup for the welding experiment. The prototype was connected to the laptop via PassBox2 and the MR driver. Based on the information from the rotary encoder, the strategies were executed by Matlab/Simulink and the MR brake as controlled. The control cycle was 1 kHz.
The prototype was fixed to a workbench and had a cover to protect it from flying metal and sparks. The torch of the semi-automatic welding machine (Arcury160) was attached to the end effector. A 4 mm thick iron plate was used for the welding.

The experimental conditions are listed in the first four columns of Table 3. The experiment was performed under different conditions: with or without equipment, with or without path regulation, and with or without speed regulation. Velocity restriction was performed using two strategies: the feedback strategy and the proposed method employing a virtual wall.

The operator was a healthy adult male who was not skilled in welding. The operator received sufficient explanation regarding the experiment in advance. Thereafter, he evaluated the welding operation correction achieved by the device and performed welding after completely understanding details of the operation.

6. Result and discussion

The welding traces obtained for each condition are shown in the fifth column of Table 3. On some conditions, insufficient penetration was observed, hence the heat input may have been insufficient. However, the heat input was constant and was not adjusted since the purpose of this experiment is to compare the proposed methods so that all conditions become same other than control strategy. For condition A, the welding line was more uneven than other welding marks. This is because the vertical distance between the torch and the metal plate becomes constant, depending on the device, and the unevenness is considered to increase only in condition A when the device was not used.

Subsequently, the existence of a path restriction was considered. A comparison of the welding marks C, F, and G with path restrictions and the welding marks B, D, and E, without path restrictions clearly indicates that marks C, F, and G are straighter. This proves that welding that near a linear target can be performed via pass regulation. The right end of condition C is not a straight line, because it is not in the desirable welding line immediately after the start of welding. It can be seen that the line is off the desirable line at the start of welding, and the weld mark is formed so as to return to the desirable line at the beginning. After going a little to the right, most of the left side of welding line was straight.

Moreover, speed restriction was also considered. First, weld marks B were compared with D and E. The speed control applied by two strategies in D and E confirm that the thickness is constant, and the unevenness is small in comparison to welding mark B, without speed restriction. For condition B, the average hand speed was approximately 1.7 mm s$^{-1}$, which is much slower than the target of 3 mm s$^{-1}$. This suggests that spots where welding marks became unnecessarily thick occurred and that unevenness occurred. Under condition D, the average hand speed during welding was approximately 5 mm s$^{-1}$. This is thought to be because the operator tried to move the torch at 3 mm s$^{-1}$, which was below the limit of approximately 20 mm s$^{-1}$, which is the limit of speed control by feedback. We also believe that speed regulation by feedback control works as a damper element, reducing hand shake. Under condition E, the hand speed was 3 mm s$^{-1}$. As a result, welding spots with less unevenness were confirmed.

Next, we focused on conditions F and G. Under these conditions, path regulation and velocity restriction were performed, so the cleanest welding lines were expected. The actual welding lines for conditions F and G were cleaner than those for conditions A to E. These results confirm that the proposed strategy implemented using the prototype promotes clean and straight welding.

Figure 12 shows the time variation of the displacement in the x direction under conditions F and G. As shown in the figure, welding was performed at a constant speed (3.0 mm s$^{-1}$) under condition G. However, the welding line obtained under condition F was less uneven. It is considered that this was mainly due to the slight backlash and deformation of the prototype. In the experiment, the operator moves the torch against the restriction by the prototype. In case of the feedback velocity control, the torch moves with respect to the pushing force of the operator due to insufficient speed restriction. On the other hand, since the torch does not move with the virtual wall strategy, the pushing force from the operator became larger and the posture of the torch changed due to slight backlash and deformation. As a result of that, on condition F was the cleanest welding line.
| Condition and result of actual welding experiment. |
|--------------------------------------------------|
| w or w/o device | w or w/o path restriction | w or w/o velocity restriction | Welding line |
|-----------------|---------------------------|-------------------------------|--------------|
| A               |                           |                               |              |
| B               | ○                         |                               |              |
| C               | ○                         | ○                             |              |
| D               | ○                         | ○                             | (Feedback)   |
| E               | ○                         | ○                             | (Virtual moving wall) |
| F               | ○                         | ○                             | (Feedback)   |
| G               | ○                         | ○                             | (Virtual moving wall) |
7. Conclusions

We proposed a welding teaching device that uses an MR brake to improve the device’s safety and adaptability to the welding environment. In addition, we developed and evaluated a prototype with two DOFs. The evaluations included the path rendering, velocity restriction, and actual welding experiments. The results show the effectiveness of the proposed method. The following main conclusions can be drawn from the development and results.

- With respect to path rendering, it is possible to present routes with an accuracy of 1 mm or better using a prototype with an MR brake device and rotary encoder.
- With respect to speed control, although the minimum speed that can be regulated by ordinary feedback control is greater than the speed required for welding work, the proposed moving wall method can regulate the speed required for welding.
- In an actual welding environment, path and speed regulation have the effect of making welding lines clean.

These characteristics make the proposed force feedback device feasible for application to welding instruction. In addition, the proposed method has passive characteristics and positional accuracy, so it is expected to be adaptable to other applications.

In the future, we will confirm the effectiveness of the welding teaching method and extend the proposed method to three DOFs. As for confirmation of teaching effectiveness, comparative experiment will be conducted. Multiple welding beginners are divided into two groups, one with the training device and another is without the device, and evaluate welding skills after training. To expand of the DOF, proposed method will be applied to the delta type parallel link mechanism [13]. Using MR brakes as three actuators of the delta type parallel link mechanism, and two of them generate a braking torque if the end effector need to be restricted to one DOF. Utilizing this phenomenon, the proposed method can be applied to three DOFs.

Appendix A the parameters and variables

Table A1. List of parameters and variables.

| Symbol | Definition |
|--------|------------|
| \( l_i \) [mm] | Length of the member |
| \( \theta_i \) [rad] | Angle between members |
| \( \alpha \) [rad] | Angle between \( P_3 P_4 \) and \( P_4 P_5 \) |
| \( \beta \) [rad] | Angle between \( P_3 P_4 \) and horizontal line |
| \( L \) [mm] | Length of \( P_1 P_4 \) |
| \( y_0 \) [mm] | Reference line coordinate |
| \( \Delta y \) [mm] | Allowance width |
| \( F \) [N] | Force at end effector |
| \( F_x, F_y \) [N] | \( x \), \( y \) component of \( F \) |
| \( F_{1, 2} \) [N] | Braking force of MR brake |
| \( \gamma \) [rad] | Angle between \( F \) and horizontal line |
| \( \delta_1, \delta_2 \) [rad] | The angle between \( F_1, F_2 \) and horizontal direction |
| \( \tau_{1, 2} \) [Nm] | Brake torque of MR brakes |
| \( x \) [mm] | Position of end effector in \( x \) direction |
| \( y \) [mm] | Position of end effector in \( y \) direction |
| \( V \) [mm/s] | Speed of end effector |

Figure 13. Multiply \( F_1 \) and \( F_2 \) with the distances from \( P_1 \) to \( P_3 P_5 \) and from \( P_2 \) to \( P_4 P_5 \) and convert them to brake torques.

Appendix B. Force control

We succeeded in rendering the welding path and restricting welding velocity with on–off control of an MR brake device, as described in the main text of the paper. It is necessary to consider braking force control to achieve a more widespread application of the proposed method. For this purpose, a force control strategy is described in this appendix.

Force control strategy

For controlling the braking force at the end effector, it is necessary to convert the command braking force at the end effector into the torque of the MR brakes. This section describes this conversion process. The parameters required for the calculation are depicted in figures 13 and 14.

First, \( F_x \) and \( F_y \), which are the \( x \)- and \( y \)-components of \( F \), are calculated using the following equations:

\[
F_x = F \cos \gamma
\]  \hspace{1cm} (A1)

\[
F_y = F \sin \gamma
\]  \hspace{1cm} (A2)

Subsequently, \( F_x \) and \( F_y \) are converted into the braking force applied by the MR brakes. The torque generated at \( P_1 \)
The command value and measured value of force control experiments are shown in Figure 14. The experimental results are shown in Figure 15.

**Figure 14.** Decompose $F$ into its $x$- and $y$-component $F_x$ and $F_y$; thereafter, set $F_1$ parallel to $P_1P_2$ and $F_2$ parallel to $P_3P_4$, based on $F_x$ and $F_y$.

**Figure 15.** Command value and measured value of force control experiments.

**Table A2.** Mean measured values and command values.

| Command value $F_i$ [N] | 0.00 | 2.50 | 5.00 | 10.0 |
|-------------------------|------|------|------|------|
| Average value of measured value $\bar{F}_i$[N] | 1.00 | 3.14 | 5.65 | 9.05 |
| $\bar{F}_i - F_i$[N] | 1.00 | 0.65 | 0.65 | -0.95 |

**References**

[1] Katagiri M 2002 Economic consequence of population aging in Japan; effects through changes in demand structure *Singapore Econ. Rev.* 0 1–23

[2] Li X et al 2019 Effects of health status on work exit and absenteeism among the older working population in China: a secondary analysis of a cohort sample *BMJ Open* 9 e024115

[3] Sadahiro K, Honda S, Miyata S, Sho Y, Sawaguchi N and Kikuchi K 2018 Robotic welding system for shipbuilding *Robot. Comput. Integr. Manuf.* 67 61–65

[4] Lee D, Ku N, Kim T-W, Kim J, Lee K-Y and Son Y-S 2011 Development and application of an intelligent welding robot system for shipbuilding *Rob. Comput. Integr. Manuf.* 27 377–88

[5] Chen S J et al 2015 Machine-assisted travel speed control in manual welding torch operation *Int. J. Adv. Manuf. Technol.* 76 1371–81

[6] Asai S, Ogawa T and Takebayashi H 2012 Visualization and digitization of welder skill for education and training *Weld. World* 56 26–34

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[7] Oz C, Ayar K, Serttas S, Iyibilgin O, Soy U and Cit G 2012 A performance evaluation application for welder candidate in virtual welding simulator Procedia Social Behav. Sci. 55 492–501

[8] Fast K, Gifford T and Yancey R 2004 Virtual training for welding Third IEEE and ACM Int. Symp. on Mixed and Augmented Reality Arlington, VA, USA pp 298–9

[9] Kobayashi K, Ishigame S and Kato H 2003 Skill training system of manual arc welding Entertainment Computing, IFIP — the International Federation for Information Processing ed R Nakatsu and J Hoshino (Berlin: Springer) vol 112 pp 389–396

[10] Mavrikios D, Karabatsou V, Fragos D and Chryssolouris G A prototype virtual reality-based demonstrator for immersive and interactive simulation of welding processes 2006 Int. J. Computer Integ. Manuf. 19 294–300

[11] Teo C L, Burdet E and Lim H P 2002 A robotic teacher of Chinese handwriting Proc. 10th Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002 Orlando, FL, USA pp 335–41

[12] Yoshikawa T and Henmi K 2000 Human skill transfer using haptic virtual reality technology Experimental Robotics VI. Lecture Notes in Control and Information Sciences vol 250 (Berlin: Springer) pp 351–360

[13] Okui M, Kobayashi M, Yamada Y and Nakamura T 2018 Delta-type 4-dof force-feedback device composed of pneumatic artificial muscles and magnetorheological clutch and its application to lid opening Smart Mater. Struct. 28 64003

[14] Furusho J, Sakaguchi M, Takesue N and Koyanagi K Development of ER brake and its application to passive force display 2002 J. Intell. Mater. Syst. Struct. 13 425–9

[15] Kikuchi T, Xinghao H, Fukushima K, Oda K, Furusho J and Inoue A 2007 Quasi-3-DOF rehabilitation system for upper limbs: its force-feedback mechanism and software for rehabilitation 2007 IEEE 10th Int. Conf. on Rehabilitation Robotics Noordwijk pp 24–27

[16] Liu Y, Yuan J, Dong Y, Zhaoa X and Yin J 2017 Enhanced temperature effect of electrorheological fluid based on cross-linked poly(ionic liquid) particles: rheological and dielectric relaxation studies Soft Matter 13 1027–39

[17] Lee J et al 1999 Effect of polymerization temperature on polyacrylamide-based electrorheological suspensions Colloid Polym. Sci. 277 73–76

[18] Wu X, Xiao A, Tian Z, Chen F and Jian W 2016 Effect of particle characteristics and temperature on shear yield stress of magnetorheological fluid J. Magn. 21 244–8

[19] Okui M, Iikawa S, Yamada Y and Nakamura T 2018 Fundamental characteristic of novel actuation system with variable viscoelastic joints and MR clutches for human assistance J. Intell. Mater. Syst. Struct. 29 82–90

[20] Omron corporation https://automation.omron.com/en/us/products/family/E6B2-C

[21] Fuji Latex Co., Ltd. https://www.fujilatex.co.jp/en/softabsorber_main_category/mrf/

[22] MIS Corporation https://www.mttis.co.jp/items/model_base_design/s-box2/

[23] KETENCE Corporation https://www.keyence.com/products/microscope/high-speed-microscope/vw-9000/