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Sensory Evaluation of Friction and Viscosity Rendering with a Wearable 4 Degrees of Freedom Force Feedback Device Composed of Pneumatic Artificial Muscles and Magnetorheological Fluid Clutches

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Abstract: With the progress in virtual reality technology, various virtual objects can be displayed using head-mounted displays (HMD). However, force feedback sensations such as pushing against a virtual object are not possible with an HMD only. Focusing on force feedback, desktop-type devices are generally used, but the user cannot move in a virtual space because such devices are fixed on a desk. With a wearable force feedback device, users can move around while experiencing force feedback. Therefore, the authors have developed a wearable force feedback device using a magnetorheological fluid clutch and pneumatic rubber artificial muscle, aiming at presenting the elasticity, friction, and viscosity of an object. To date, we have developed a wearable four-degree-of-freedom (4-DOF) force feedback device and have quantitatively evaluated that it can present commanded elastic, frictional, and viscous forces to the end effector. However, sensory evaluation with a human has not been performed. In this paper, therefore, we conduct a sensory evaluation of the proposed method. In the experiment, frictional and viscous forces are rendered in a virtual space using a 4-DOF force feedback device. Subjects are asked to answer questions on a 1- to 7-point scale, from 1 (not at all) to 4 (neither) to 7 (strongly). The Wilcoxon signed rank test was used for all data, and answer 4 (neither) was used as compared standard data. The experimental results confirmed that the user could feel the presence or absence of viscous and frictional forces. However, the magnitude of those forces was not sensed correctly.

1. Introduction

With the development of virtual reality (VR) technology, users can recognize various virtual objects while moving in a space such as a room. They do this by wearing a head-mounted display (HMD). However, with HMD alone, touching an object in the VR space does not provide force and tactile sensations, as in real space. Therefore, it is difficult to grasp the mechanical characteristics of the object. Focusing on haptic technology, general haptic devices are desktop ones such as Touch, by 3D Systems[1)], and Omega 7, by Force Dimension[2)]. A desktop device is used by placing it on a desk, so there is an advantage that the user does not support the weight of the device. However, the user cannot move in the virtual space because the device is fixed. If a wearable device was developed, it would be possible to present haptics in wide space. Many wearable haptic devices have been studied thus far[3-7)]. However, because these devices provide force feedback through a motor and reduction gear, their

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back-drivability is low. Therefore, the force-rendering quality in the free-to-move state is low. A method using a direct-drive motor is also conceivable, but an increase in the mass of the motor itself would be inevitable.

As an alternative to a motor and reduction gear, the authors developed a wearable force feedback device that uses a magnetorheological (MR) fluid clutch and pneumatic rubber artificial muscle, aiming at the presentation of high-quality free space[8-10]. This proposed system is able to render the elasticity, friction, and viscosity of an object. So far, we have developed a wearable four-degree-of-freedom (4-DOF) haptic device and conducted a quantitative evaluation. The results showed the ability to present various forces at the end effector. However, the qualitative evaluation was not performed using an HMD and combining vision and force feedback in the virtual space.

Therefore, in this paper, we conduct a qualitative evaluation of the proposed method by rendering frictional and viscous forces in a virtual space by combining a 4- DOF force feedback device and an HMD.

2. Force Feedback Method

2.1 Overview of the proposed joint

Figure 1 shows a schematic diagram of a force feedback joint that with an MR fluid clutch and artificial muscle. The proposed system consists of pneumatic artificial muscle, an MR clutch, a wire, a pulley, and an attachment part. The pneumatic artificial muscle is used as a variable elastic element, and the MR clutch is used as a variable torque-transmitting element. Figure 2 shows a schematic diagram of the presentation method for the free-to-move state for

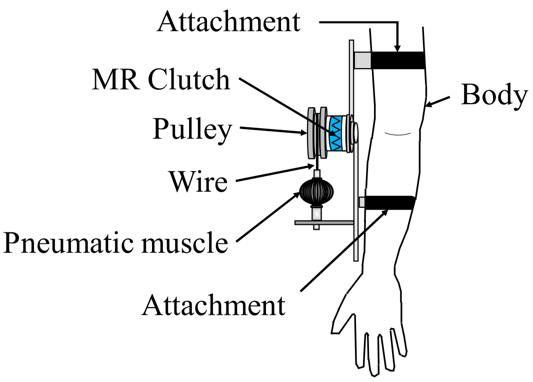


Fig. 1 Schematic diagram of joint for force feedback

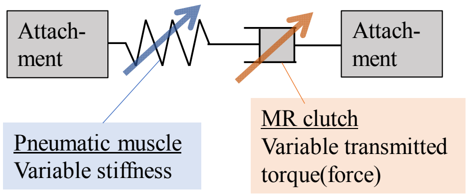
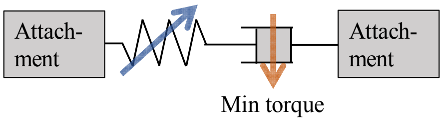
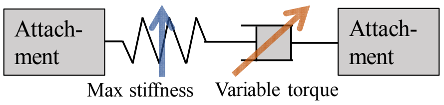
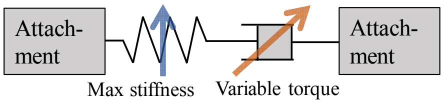
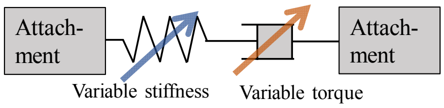
Equivalent system		2 attachments are connected via pneumatic muscle and MR clutch.
Free to move		No stiffness or force transmitted (MR clutch is off and in slippage mode)
Friction force rendering		MR clutch changes transmitting torque to render friction force to end effector.
Viscous force rendering		MR clutch changes transmitting torque to render viscous force to end effector.
Stiffness rendering		Pneumatic muscles are pressurized to achieve desirable stiffness at end effector. MR clutch changes transmitting torque to cancel nonlinearity of pneumatic artificial muscle stiffness.

Fig. 2 Function of the pneumatic muscle and MR clutch, considering rendered force

friction, viscosity, and elasticity. The characteristics of the object to be rendered are expressed by changing the state of the artificial muscle and the transmitted torque of the MR clutch.

2.2 Pneumatic artificial muscle

Figure 3 shows a schematic diagram of the pneumatic artificial muscle[11)]. This muscle is composed of a carbon fiber sheet and latex rubber. When air pressure is applied, it contracts in the axial direction and expands in the radial direction. The variable stiffness characteristic of the artificial muscle is utilized for force rendering.

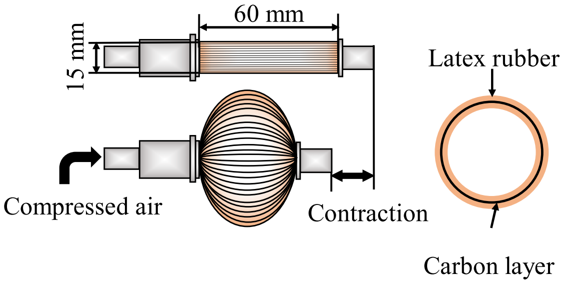


Fig. 3 Schematic diagram of pneumatic artificial muscle

2.3 Magneto rheological brake

Figure 4 shows the appearance and internal structure of the MR fluid clutch used in the device. This clutch is composed of disks that enclose a magnetic viscous fluid and rotate in conjunction with an internal core, and a coil that generates a magnetic field[12)]. When a magnetic field is generated, clusters of magnetic particles are formed perpendicular to the direction of disk rotation. The clusters are cut by rotating the disk, and the shear stress is exerted as braking torque. The torque can be controlled within tens of milliseconds[13)].

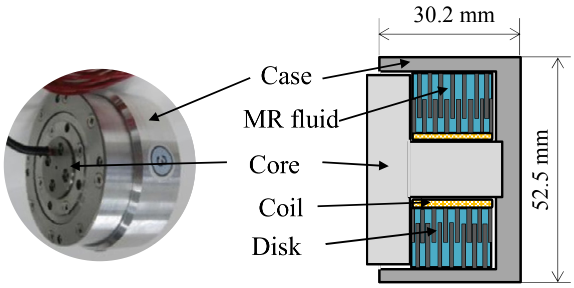


Fig. 4 Overview of MR fluid clutch

2.4 4-DOF prototype

Figure 5 shows the wearable 4-DOF force feedback device developed by the authors[8)]. The 5.5-kg prototype has four proposed active joints, each of which has a pneumatic muscle and an MR clutch.

This device calculates the required torque at each joint using the Jacobian from the target's rendering force at the end effector.

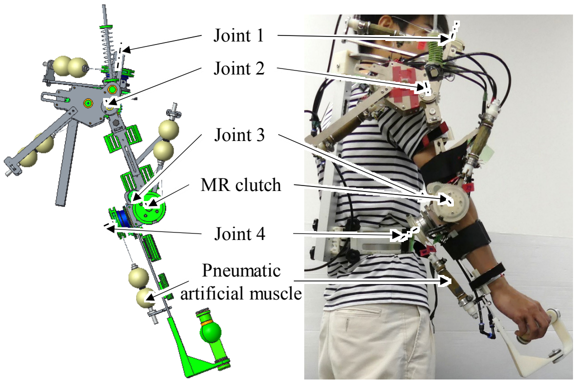


Fig. 5 Overview of force feedback device

3. Friction rendering experiment

3.1 Objective

The objective was to qualitatively evaluate the friction presentation ability of the proposed method. In the experiment, the subjects wore the HMD and force feedback device, and a friction force was rendered to them. Then, they answered the questionnaire.

3.2 Set up

Figure 6 shows the experimental setup. Oculus Rift and Kinect v2 are connected to a measurement PC, and the force feedback device is connected to a control PC. In the experiment, the measurement PC acquired the position and orientation of the HMD, which was the position of the subject's right hand. It also constructed a virtual space using Unity and showed it to the subject through the HMD. The control PC controlled the device according to the information from the measurement PC.

Figure 7 shows an example of the image seen by the subject. The red sphere represents the subject's hand, and the blue box is the frictional object. When contact between the subject's hand and the object in the virtual space is detected, the result is sent to the control PC, which controls the prototype based on the judgment.

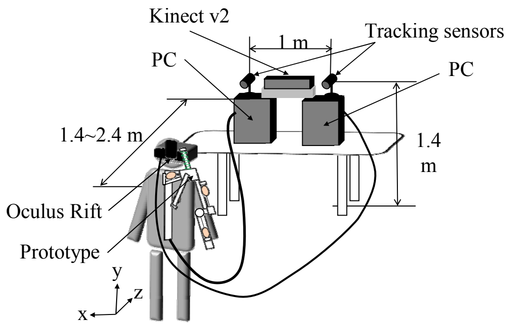


Fig. 6 Experiment setup

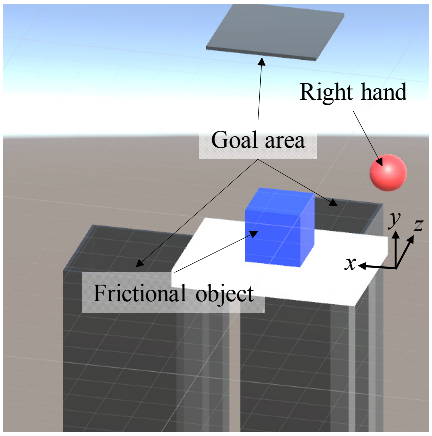
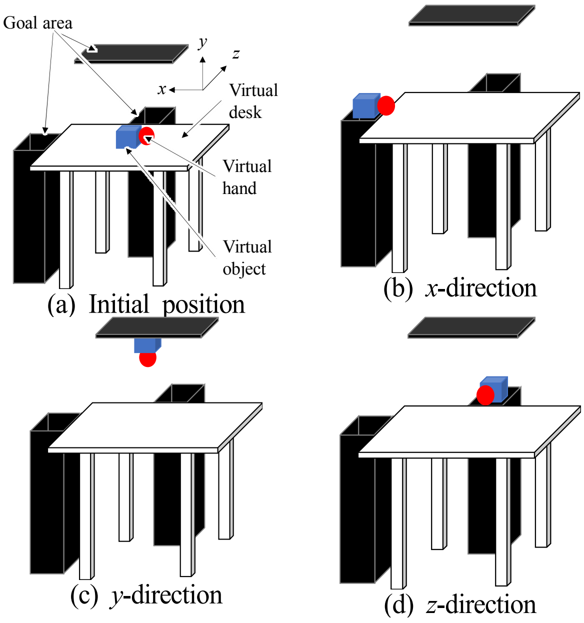


Fig. 7 VR space for rendering friction



(a) Initial position (b) *x*-direction (c) *y*-direction (d) *z*-direction

Fig. 8 Behavior of subjects for the experiment

3.3 Procedure

The virtual space used in the experiment is shown in Fig. 8. Three forces are presented: 3, 6, and 9 N. The subject pushes the virtual object with the virtual right hand and moves it to the goal area. The virtual object is pushed in the x- and z-directions until it leaves the virtual desk, after which the object falls because of gravity, and then the operation ends. In the y-direction, the motion ends when the virtual object is pushed into the goal area. The experimental procedure is as follows.

Render the reference 6 N to the subject.

Render the 3-, 6-, or 9-N friction force to the subject. The commanded friction force is not told to the subject.

Perform steps (1) and (2) 15 times each in the x-, y-, and z-directions, for a total of 45 times.

At the end of the experiment, the subjects were asked to complete a seven-point questionnaire (7: strongly agree, 4: neither, 1: not at all). The contents of the questionnaire are shown in the second row of Table 1. The subjects in this experiment were seven males in their twenties. All of the procedures used in this research were approved by the Ethics Committee of the Faculty of Science and Technology of Chuo University (approval number 2017-30).

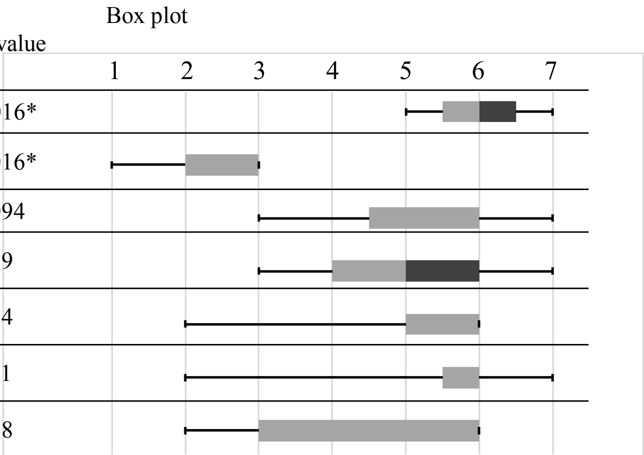
3.4 Result and discussion

The results are shown in Table 1. The Wilcoxon signed rank test was used for all data, and answer 4 (neither) was used as compared standard data. The fifth and sixth columns show the results of the experiments. P-values were calculated for each question using the Wilcoxon signed rank test based on “4: Neither”. The significance level was set to 5%, as indicated by *. In the box plot, the straight lines at the top and bottom indicate the maximum and minimum values, respectively. The bars indicate the 25th and 75th percentiles, and the line at which the color depth changes indicate the median.

There was a significant difference in Q1 ($p = 0.016$). Therefore, it can be said that the subject could recognize the frictional force rendered by the device. A significant difference was observed in Q2 ($p = 0.016$). From previous studies[10], it was confirmed that the device requires an end effector displacement of about

Table 1 Questionnaire and result of the friction force rendering experiment

	Questionnaire	p-value
Q1	Did you feel the friction force from the virtual object?	0.016*
Q2	Did you feel the delay of the feedback force compared with the visual information?	0.016*
Q3	Did you feel the difference in the friction force?	0.094
Q4	Did you feel the difference in the friction force when pushing the right-side surface of the virtual object?	0.19
Q5	Did you feel the difference in the friction force when pushing the bottom surface of the virtual object?	0.14
Q6	Did you feel the difference in the friction force when pushing the front surface of the virtual object?	0.11
Q7	Did you feel the friction force when the hand was detached from the virtual object?	0.38



* $p < 0.05$

several tens of millimeters to reach the target frictional force. Therefore, a time delay was inevitable, but it was confirmed that this delay did not affect human sensing. There was a significant trend in Q3 (p = 0.094) but no significant difference in Q4, Q5, and Q6 (p = 0.19, 0.14, 0.11). This indicated that the range that the prototype was able to render was small for human sensing. There was no significant difference in human sensitivity. Q7 (p = 0.38). In this device, the mechanical friction of the member and the base frictional torque of the MR fluid clutch were generated, even in the free-to-move condition. However, the effect was not significant for human sensing.

4. Viscous force-rendering experiment

4.1 Objective

The purpose of the experiment was to qualitatively evaluate the viscous rendering ability of the proposed method. As in the friction force-rendering experiment, the subjects wore the HMD and force feedback device, and a viscous force was rendered. Then, the subjects answered the questionnaire.

4.2 Setup and procedure

The setup was the same as for the friction rendering experiment. Figure 9 shows the virtual space used in the experiment. The viscous object was water-like object that moved in an undulating manner. When the end effector was in the object, a viscous force was rendered to it. A refraction phenomenon occurred when a subject’s right hand entered the viscous object, so the subject could visually recognize the viscosity.

In this experiment, the movement direction was not specified. That is because the viscous force was generated by the movement of the subject, and it was difficult to determine its direction. The viscosities to be set were 20, 30, and 40 N·s/m in the x-, y-, and z-directions, respectively, and were defined as small, medium, and high in order of increasing viscosity.

The experimental procedure was as follows:

The subject touches the virtual object with only the HMD, without the force feedback device.

The subject wears the force feedback device and three types of force are rendered: low, medium, and high viscosity. At this time, the subject is told the magnitude of the rendered viscosity.

The medium reference viscosity is rendered.

A randomly selected viscosity (small, medium, or high viscosity) is rendered. At this time, the subject is not told the magnitude of the rendered viscosity.

Steps (3) and (4) are conducted 15 times.

At the end of the experiment, the subjects were asked to complete a seven-point questionnaire (7: strongly agree, 4: neither, 1: completely disagree). The contents of the questionnaire are shown in the second row of Table 2.

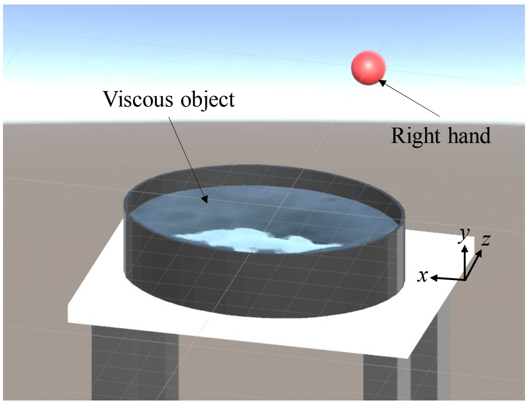


Fig. 9 VR space for rendering viscous.

4.3 Results and discussion

Table 2 shows the results of the test subjects. These results are shown in the same manner as in Table 1.

Regarding Q1, a significant difference ($p < 0.05$) was confirmed. From these results, it was found that the subjects could not feel the viscosity with the HMD only. Although no significant difference was observed for Q2, a weak tendency ($P = 0.094$) was confirmed. This indicates that the viscous force was generated. However, it was not sufficient for the subject to feel.

There was no significant difference for Q3. From this result, it could be expected that there would not be much effect on the delay of the presentation of viscosity, as in the case of friction. However, because no significant difference was confirmed in Q2, the viscosity may not have been recognized in the first place. No significant difference was confirmed in Q4, and it is believed that the difference in the viscosity magnitude could not be recognized. In addition, there was no significant difference for Q5. In other words, the result was that the resistance after the subject released the hand was low. It should be noted that this result may not recognize viscosity, like Q3.

From the above, we could not confirm the effect of a viscous force on human sensation.

5. CONCLUSION

Friction and viscosity rendering experiments were conducted in virtual space using a 4-DOF force feedback device composed of a pneumatic artificial muscle and an MR clutch. From the results, it was confirmed that the subjects could recognize a frictional force received from the virtual object, although they could not recognize its magnitude. As for viscosity, although previous studies have confirmed that the quantitative evaluation of viscosity can be achieved, a significant result could not be obtained in this study.

The results clarified that future work is required to improve the range of friction and viscosity.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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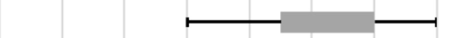
Table 2 Questionnaire and result of the viscous force rendering experiment

	Questionnaire	p-value	Box plot 1 2 3 4 5 6 7
Q1	Did you feel the viscous force from the virtual object? (Only with visual information)	0.031*	
Q2	Did you feel the viscous force from the virtual object?	0.094	
Q3	Did you feel the delay of the feedback force compared with the visual information?	0.25	
Q4	Did you feel the difference in the viscous force when touching the virtual object?	0.43	
Q5	Did you feel the viscous force when the hand was detached from the virtual object?	0.16	

* p <0.05

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