Resistive-Force Presentation Device Using Magneto-Rheological Fluid for Wrist-Joint Stiffness Control

Taiki Funabiki, Yoichi Yamazaki, and Masataka Imura(✉)

Kwansei Gakuin University, 2-1 Gakuen, Sanda, Hyogo 669-1337, Japan
`m.imura@kwansei.ac.jp`

Abstract. MR fluid has high speed responsiveness and shows a shear response in a direction perpendicular to the magnetic flux direction, when a magnetic field is applied. In this research, we propose a compact and lightweight wrist-mounted resistance force presentation device utilizing the characteristics of MR fluid. By controlling the magnetic flux density applied to the rubber tube filled with MR fluid, the resistance force is presented by increasing the rigidity of the wrist joint.

Keywords: Haptic display · Wearable device · Magnetorheological fluid

1 Introduction

Virtual reality (VR) technology is becoming increasingly popular. The major difference between VR space and real space is the lack of haptic feedback: when a user touches an object in VR space, the user you do not get the same sensation that comes with touching an object in real space. This lack of haptic feedback severely compromises the user's immersion in VR space. Presentation of haptic sense to the user is thus an essential element for practical use of VR space in medicine, entertainment, and other fields.

The aim of this study is to develop an easily handled, light-weight, highly responsive force feedback device that uses a relatively small force to present a resistance force. These features allow users to operate the device for a long time with little stress and easily experience a deep feeling of immersion.

Resistance force is generated when movement is hindered by external factors, e.g., the reaction force when touching an object, wind pressure, and resistance to movement in water. Our proposed design minimizes the increase of moment of inertia by attaching the device at a position close to the center of rotational motion and presenting the resistance force by limiting the rotational motion of the joint. To do the latter, we use magneto-rheological (MR) fluid, which can control rigidity arbitrarily.

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2 Related Works

Force-feedback devices that have been developed to date may be roughly divided into two types: active and passive.

The active type presents force directly to a part of the user's body by means of an actuator such as a motor. The active type has the advantage of being relatively easy to implement. The active type allows users to interact with real space from the VR side independently of the user's state. Disadvantages of the active type come from the direct presentation of force by the actuator, which is likely to cause injuries, and the large actuator required to present a large force, which increases the weight.

The passive method involves force feedback by a passive force element such as a brake when the user takes an action. A passive device is intrinsically safe, because the force-presenting part is a passive element. Unfortunately, the presentation of force in a passive device depends on the user's movement, which limits the freedom of VR/real-space interaction. For example, it is possible for the user to have the sensation of touching a ball, but it is not possible for the user to have the sensation of being hit by one. Therefore, the range of expression of passive devices is narrower than that of active devices.

From the viewpoint of installation, force-feedback devices can be divided into grounded and ungrounded types.

A grounded device is one that is fixed to the work space. Typical examples are Phantom [2] and SPIDAR [8]. This implementation method is mainly used for large devices. It has the advantage of being able to exhibit stable performance precisely. However, its use is limited by the availability of a place to install the device.

Ungrounded devices are those that are not installed on the ground. Typical examples are devices that are light enough to be grasped by hand [10], devices that present multiple haptics using a drone [5], and wearable devices that users attach to their own bodies [6,9]. The advantage of the non-grounded device is that there are no restrictions on its location. Meanwhile, the force that can be presented is smaller than for the grounded type, the device is complex to install and the force is not stable.

Some force-feedback devices use the resistance acting on human joints by arbitrarily changing the joint's stiffness from the outside, thus changing the difficulty of bending the joint. There is a method using dilatancy by air aggregation for reproduction of resistance force [4,6], but there is a problem that the response is very low because air is moved.

3 Proposed Method

In both real space and VR space, work is often done by hand, and feedback to the hand is essential for such work to be accomplished smoothly. Therefore, the user's hands were chosen as the target of resistance presentation in this research.

VR equipment often places a severe burden on the user. When the device is worn, it moves in the same way that the user does, so the moment of force

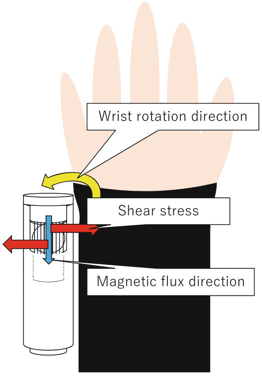

Fig. 1. Principle of resistance presentation

increases. This makes the device feel heavy. In addition, the procedure for attaching and detaching the device to the user is often complicated, making it difficult to put on unassisted.

One way to mitigate the increase in moment is to mount the device as closely as possible to the center of rotation of the motion (in this case, a human joint), thereby minimizing the moment of inertia. We chose to focus on the wrist, a place where the device can be attached fairly easily.

To present resistance, we sought a method that would be lightweight, would be able to increase joint stiffness instantaneously, and would not obstruct free movement of the joint except when presenting. MR (Magneto-Rheological) fluid is a material satisfying these three requirements.

MR fluid is a colloidal dispersion of 10 μm ferromagnetic particles in oil. When a magnetic field is applied, the particles form a chain structure along the lines of magnetic force, and the fluid exhibits a shear stress in a direction perpendicular to the chain structure. The magnitude of the shear stress corresponds to the strength of the applied magnetic-flux density; generally, its maximum value is several tens of kPa. MR fluid response-time is a few milliseconds; this is much shorter than a human's reaction time, allowing real-time control of rigidity [3].

The principle of resistance presentation is shown in the Fig. 1. A device equipped with a rubber tube filled with MR fluid (hereafter referred to as an MR tube) is attached to the wrist. Applying the strong magnetic field to the MR tube increases the viscosity of the MR fluid, and the induced shear stress resists movement of the wrist.

4 Device Development

The device configuration and prototype device are shown in the Fig. 2, the device in use is shown in the Fig. 3.

To adjust the viscosity of the MR fluid, it is necessary to control the magnetic flux density applied. The obvious method of doing this would be to use an

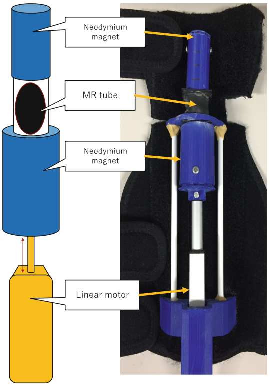

Fig. 2. Device configuration and prototype device

Fig. 3. Device in use

electromagnet. However, this is not feasible if the device is to be light-weight and wearable, because a huge electromagnet would be required to produce the necessary flux density. We use two high-field permanent magnets, one above and one below the MR tube. Fixing the upper magnet and moving the lower one up and down with a linear actuator strengthens or attenuates the magnetic flux density in the tube as desired.

Since the proposed device uses a permanent magnet instead of an electromagnet, a magnetic field is present even when sense of resistance is not required. To reduce the magnetic flux density in the deactivated state, a spring is inserted between the fixed upper magnet and the MR tube. This spring contracts when the lower magnet is brought near the MR tube by the linear actuator, and the magnetic flux density applied to the MR fluid increases. In the deactivated state, the extension of the spring increases the distance from the MR tube to the magnet and decreases the magnetic flux density.

Rather than a pure MR fluid, we used an MRα fluid [7], that is a mixture of MR fluid and non-magnetic material. The inclusion of non-magnetic material increases the hardness of the MR fluid when solidified and reduces the weight of the fluid per unit volume. In the present case, polystyrene spheres with a particle size of 0.5 mm were mixed in as a non-magnetic material. The mixing ratio was determined so that the volume ratio of MR fluid to polystyrene was 1:1.

We used the MR fluid (MRF-140CG, LORD Corporation) [1]. It exhibits a shear stress of 0–60 kPa as the applied magnetic flux density varied from 0–1 T. The MRα fluid was enclosed in a highly oil-resistant fluororubber tube with an outer diameter of 22 mm and an inner diameter of 20 mm.

To control the magnetic flux density, we used two neodymium 40 permanent magnets. The upper magnet had a diameter of 16 mm and a height of 20 mm and the lower magnet a diameter of 20 mm and a height of 30 mm. The magnet and motor cases were each made by PLA with a 3D printer.

Table 1. Result of Experiment 1

Range [mm]	Magnetic flux [mT]
0	630
10	353
20	124
30	65

A wrist fixing band was used to secure the resistance-presentation device to the user's wrist. We used a wrist holder (KA085, Medical Project Co., Ltd) as a restraint to secure the device to the wrist. It is desirable to use a rubber fixing-band that can be adjusted to fit the user's wrist. However, if rubber with high elasticity is used, it will bite into the wrist as the wrist moves, and a sense of restraint occurs. This feeling of restraint could be reduced by using rubber that is not highly stretchable. In practice, we found that the undesirable sense of restraint was strong enough when the fixed orthosis was used as it was, so the unnecessary fixing band was removed.

5 Experiments

5.1 Experiment 1: Measurement of Magnetic Flux

An experiment was conducted to confirm whether the magnetic flux density could be controlled by the prototype mechanism.

We measured the magnetic flux density under the MR tube of the prototype device with a teslameter (BST-200, Beijing Ever Good Electronic) having a range of 0–2000 mT, and a sensitivity of 0.1 mT. We conducted measurements when the distances between the MR tube and the lower magnet were 30 mm, 20 mm, 10 mm, and 0 mm.

The results are shown in the Table 1. The maximum value of the magnetic flux density was about 9.7 times the minimum value. This confirmed that the magnetic flux density could be controlled by the proposed mechanism, and that the amount of change is sufficient for our purposes.

5.2 Experiment 2: Measurement of Bending Stiffness

We measured the hardness of bending the prototype's MR tube, which is the source of resistance to wrist motion. As shown in the Fig. 4, we fixed one side of the device, applied a load to the other, and measured the resulting deformation. The bending stiffness K was calculated according to

$$K = \frac{P}{\delta}, \tag{1}$$

where P is the load and δ is the device displacement. The distances between the MR fluid and the lower magnet were the same as in the experiment 1.

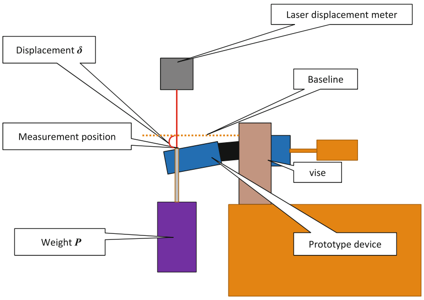

Fig. 4. Arrangement of Experiment 2

Table 2. Result of Experiment 2

Range [mm]	Displacement [mm]	Bending stiffness [N/mm]
30	18.67	1.07
20	18.46	1.08
10	17.95	1.11
0	17.53	1.14

To apply a torque of approximately 1 Nm, a 2 kg weight was attached at a position 50 mm from one end of the MR tube. A laser displacement sensor (ZX2-LD100, OMRON) was used to measure the deformation of the MR tube. The measurement range was 35 mm and the accuracy was 5 µm.

The results are shown in the Table 2 and Fig. 5. The bending stiffness was found to increase with the applied magnetic flux density, as expected. However, the difference in bending stiffness was small. This is because the fluororubber used for sealing does not expand or contract much, and is difficult to bend even when the magnetic field is not strong. By making the material stretchable, for example by wrinkling it like a bellows, the bending stiffness due to the fluororubber could be reduced.

5.3 Experiment 3: Subjective Evaluation

An experiment was conducted to investigate whether it is possible to distinguish between the activated and deactivated states.

The subjects were five males in their twenties. We measured the wrist circumference, forearm circumference, and forearm length of each subject. The subjects were asked to operate the device, with the device in the activated state or deactivated state. Thirty trials were performed in random order, fifteen for each state. In the activated and deactivated states, the distances between the MR fluid and the lower magnet were 0 mm and 30 mm, respectively. During the trial, the state of the device was not visible to the subjects. Sound was played through headphones, so that the state could not be determined from the driving sound of the device. The subjects were asked to move their hand freely and then asked in which state they believed the device to be.

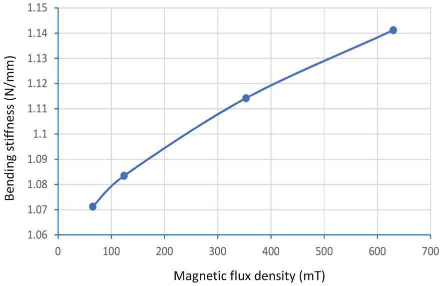

Fig. 5. Result of Experiment 2

Table 3. Result of Experiment 3

Subject	Perimeter of wrist [cm]	Perimeter of forearm [cm]	Length of forearm [cm]	Correct answer rate [%]
A	22	25	30	73.3
B	22	24	28	73.3
C	22	30	30	86.7
D	26	30	33	63.3
E	25	27	30	66.7

The results are shown in the Table 3. All the subjects achieved a correct answer rate that exceeded the chance level. The result showed that the two states could be identified with reasonable accuracy. However, an average accuracy rate of about 72.7% is still low for a practical resistance-presentation device, so further development for increasing resistance force will be necessary. We found that the correct answer rate was independent to the size of the user's arm.

After the experiment, we asked the subjects for their impressions of the force and restraint presentation in the experiment. Wrist movement direction had not been limited, and the subjects had been instructed to move their wrists freely. They reported that it was easy to perceive if they rotated their wrist joints round. And there was also an opinion that the bands for fixing the device to the wrist were annoyed and restrained smooth moving of the subjects' hand.

6 Conclusion

In this research, to develop a lightweight and easy-to-use force-feedback device, we focused on joint-stiffness control. Since MR fluid can rapidly and controllably change its stiffness in response to magnetic flux density, we proposed using an MR-fluid tube and a movable neodymium magnet in a highly responsive, lightweight resistance-presentation device attached to the wrist joint. We experimentally confirmed the performance and controllability of the magnetic flux density control mechanism of the prototype device. In addition, we conducted experiments confirming that the bending stiffness of the MR tube, which causes a sense of resistance, could be controlled by the application of magnetic flux density. The subjective evaluation revealed that users could correctly perceive the resistive state of the device with a probability significantly higher than chance.

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