Abstract—In this study, we developed a virtual cycling system (VR Bike) using a magnetorheological fluid brake (MRB). This system consists of a bike, the MRB, a 3-D projector, a screen, a controller, and a sound device. Users can drive the bike in virtual worlds with vision, sound, and reaction force on its pedal. We have developed a cylindrical MRB in the previous study, and it was utilized as the torque generator for the pedaling resistance of the VR Bike. This system is useful for aerobic exercise device. In this paper, we discussed torque control methods of the MRB. A braking torque generated with a constant current input normally changes depending on the rotational speed of the MRB. However, torque compensation based on the velocity feedback reduced the error between reference torques and output torques. We also conducted sensory evaluation tests for young healthy male subjects. In their experiments, difference thresholds of the pedaling forces are about 1 ~ 2 Nm for all standard stimulus.

I. INTRODUCTION

Cycling is not only a transportation method, but also a major activity for human health and sports. According to the medical articles [1]-[3], appropriate amount of aerobic exercise is effective to prevent dementia, which is one of major concerns in the aging societies [4]. It is said that the increase of blood volume in brains during mild exercises works well to prevent or decelerate the dementia [5]. The cycling is a promising candidate as such an aerobic exercise. We can find many aerobic bike-type fitness machines in fitness clubs and people who pedal a bike in a sweat.

In this study, we propose a virtual cycling system (VR Bike) which can control its vision, sound and resistance on pedals depending on the pedaling exercise of users (see Fig. 1). By putting it together a vision and a sound system, we can perceive virtual environments we will see during cycling and enjoy virtual cycling even in rooms. For patients who have physical impairments and / or cognitive impairments, there are some dangerous situations in real cycling. However, if they can ride a bike and feel virtual cycling ambience, it helps them to do mild exercise without some dangerous cases.

There exist some products for cycling simulator. For examples, Japanese automobile company, Honda has developed a virtual reality system to learn how to drive a bike and traffic rule in public roads [6]. This system is mainly used as an educational tool for children. Users can experience virtual environment during cycling. The system can control load on pedals at the start of cycling for increasing sense of reality. On the other hand, D. Kwon et al. [7] have developed a bicycle simulator which can realize 6DOF motions of the bike with a Stewart platform. They also used a combination of an AC-servomotor and a magnetorheological fluid (MRF) brake to control the pedal resistance of their system. This system has many DOFs, but it causes its large size and high cost.

When we consider a training machine for nonathletic users, it is enough to realize the resistance on the pedals of a bike. In such cases, we do not need to activate the pedals with actuators. We can find some products which utilize only brakes for examples bike-type fitness machine or Fortius T1940 (Virtual Bike Training, USA) [8] that is a bike simulator for healthy people or athletes. However, conventional electromagnet brakes or engine brakes are not suitable to control slight changes of force that we will feel during cycling in daily life. Therefore, we decided to use an MR fluid brake (MRB) as a torque generator for the pedals of the VR Bike in order to build a simple structure with high...
safety and performances in its control of resistances.

The MRFs are functional fluids respond to applied magnetic fields with changes in rheological behaviors [9]. Several kinds of the MRFs have been released by some companies. The change of shear stresses corresponding to the intensity of external magnetic fields, which we call the MR effect, is much larger than the change of shear stress caused by Newtonian viscosity of its base fluid. Additionally, the response time of the MR effect is so fast (time constant: 2-3 milliseconds). We have developed torque controllable devices, e.g., brakes, clutches, with high performances (high speed and large torque) by using electromagnets.

There are large amount of research on the rotational MR fluid devices. As the first generation of the rotational MRBs, some researchers and companies [9]-[12] have developed disc-type brakes, in which shear stresses of the MRF generated on the surface of the disc are transformed into the braking torque. At this time, magnetic fluxes should be applied to the orthogonal direction to the shear direction of fluid.

A cylinder-shaped rotor is another choice. In this paper, we call this kind of brake the cylindrical MRB. The cylindrical MRB can effectively transduce the MR effect to its braking torque because this type uses only outside surface of the cylinder and it have potential to make MRBs with a high torque, and low inertia than the disc-type MRBs. In the previous report, we developed a cylindrical MRB and evaluated its performance [13].

In this paper, we installed the cylindrical MRB in the VR Bike (Fig.1) and discuss the control method of torques as pedal reactions. In the latter half of this paper, we discuss the sensory evaluations for the difference threshold of the pedal reaction as a basic requirement of the VR Bike system.

II. TORQUE CONTROL OF CYLINDRICAL MRB

A. Target device

In the previous study, we developed a cylindrical MRB and evaluated its performance [13]. Figure 2 shows its cross sectional view. In this figure, MRF is filled in the cavities of the outer and inner surface of the rotor cylinder. The magnetic coils are put in the outside of the cylinder and generate magnetic fluxes in the orthogonal direction of the outer and inner surface of the cylinder. It contains two magnetic coils in the outer yoke of the magnetic circuit. The rotational cylinder is inserted in the MRF filled between the inner yoke and the outer yoke. The rotor cylinder is fixed with a rotor base supported by two bearings and transmits the braking torque to the output shaft. Magnetic wires wound around the two magnetic coils are serially connected so as to make opposite rotation in coils each other. Both ends of the wire are connected to a current amplifier. The output torque (braking torque) can be controlled with intensity of the electric current applied to the coils.

We used the MR3012 (BASF) as an MRF in this paper. This is the first time to use this material as a working material of the cylindrical MRB. A mathematical model to determine the relationship between the applied current and the output torque was modeled based on the experimental results in the next section.

Table I shows the specifications of the brake. The maximum torque of this device is about 10Nm with 0.7A in input current. The torque in the off-state (idling torque) is about 1.3Nm, which is mainly caused by the friction of the oil seal.

<table>
<thead>
<tr>
<th>TABLE I SPECIFICATIONS OF MRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
</tr>
<tr>
<td>Total length (without shaft)</td>
</tr>
<tr>
<td>Length of cylinder</td>
</tr>
<tr>
<td>Thickness of cylinder</td>
</tr>
<tr>
<td>Off-state torque @ 0.0A</td>
</tr>
<tr>
<td>Rated torque @ 0.7 A</td>
</tr>
<tr>
<td>Maximum torque @ 2.0 A</td>
</tr>
<tr>
<td>Turning number of coil (Total number of 2 coils)</td>
</tr>
<tr>
<td>Electric resistance of coil (Total value of 2 coils)</td>
</tr>
<tr>
<td>Mass (with MRF)</td>
</tr>
</tbody>
</table>

B. Basic torque characteristics

We measured the basic property of the MRB in the previous study [13]. However, we used different MRF in this study in order to improve the maximum torque and reduce the input current. Then we measured the basic torque characteristics of this device in this section.

Torque testing machine we developed was used (Fig.3). The brake was fixed on an immovable plate and the output shaft was driven at a constant speed with the AC servo-motor (Direct drive motor, NSK, Japan) during tests. Braking torque was measured in real time with a torque sensor built in the belt-pulley system to transmit the driving torque from the servo-motor to the output shaft of the brake.

Figure 4 shows the relationship between the torque and the rotational velocity of the MRB for 0~0.7 A in the applied current. Rotational velocities during experiments were controlled at 0.1, 0.5, 1.0, 3.0, 5.0, and 6.28 rad/s (=1rev/s) to clarify the effects of the rotational speeds on the braking torques.
For each current, the output torque of the MRB is almost constant, but not completely constant, because of the viscosity of the fluid. It slightly increases depending on the rotational speed of the output shaft. When we use this brake as a haptic device for human sense, we should compensate this speed dependence to accurately generate desired pedaling force on users' feet.

In contrast, the required current ($I$) is calculated from the inverse function of Eq. (2) as a function of the target torque ($T_{MR}$) (Eq. (3)). This relationship is formalized by the least-squares method with torque data at a nearly-zero velocity (0.1 rad/s, see Fig. 5) as shown in Eq. (4).

\[
I = f^{-1}(T_{MR}) \quad (3)
\]

\[
I = -1.89 \times 10^{-4} \times (T_{MR})^4 + 5.22 \times 10^{-3} \times (T_{MR})^3 - 4.71 \times 10^{-2} \times (T_{MR})^2 + 2.32 \times 10^{-1} \times T_{MR} \quad (4)
\]

Finally, we can calculate the input current ($I$) for the desired torque ($T$) of the MRB as follows;

\[
I = f^{-1}(T - D \cdot \omega - T_s) \quad (5)
\]

### D. Torque control of MRB

By using Eq. (5) as a feed-forward model, the braking torque is controlled (Fig. 6). In this block diagram, the rotational speed of the brake is measured and referred to calculate the value of the speed compensation.

Figure 7 shows the experimental results of the torque control of the MRB under a variation of the rotational speed. The reference torque was set at 5 Nm for each trial. The experimental setup shown in Fig. 3 was used again. During experiments, the rotational speed of the output shaft was controlled with sinusoidal curve as shown in the dashed line of Fig. 7. The minimum speed, the maximum speed and the frequency of the sinusoidal curve are 0.0 rad/s, 6.0 rad/s, and 50 Hz, respectively.
1Hz, respectively. The solid line and the dotted line show a torque profile under the mentioned torque control with without the speed compensation, respectively. As shown in these results, the speed compensation reduced the torque error (less than 0.5 Nm) due to the viscosity of the fluid.

III. SENSORY EVALUATION FOR DIFFERENCE THRESHOLD OF PEDAL RESISTANCE

A. Experimental setup

We put a city bike on the stable floor. The MRB was connected to a crank shaft through a belt-pulley system (Fig.8). The rotational speed of the pedals is about a half of that of the MRB (reduction ratio: 1/2). This means that the maximum controllable torque on the pedal is double the maximum torque of the MRB. A monitor was installed in front of the bike and it displayed the rotational speed of the pedals (Fig.9). A click switch was attached on the handle of the bike to know the intentions of the riders.

B. Condition and subject

Young healthy 6 males were recruited as subjects. The information of the subjects is shown in the table II. The dominant legs of the subjects are right legs for all subjects. The height of the saddle was suitably adjusted for every subject.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Dominant leg</th>
<th>Age</th>
<th>Sex</th>
<th>Weight [kg]</th>
<th>Height [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Right</td>
<td>32</td>
<td>Male</td>
<td>60</td>
<td>163</td>
</tr>
<tr>
<td>B</td>
<td>Right</td>
<td>24</td>
<td>Male</td>
<td>70</td>
<td>176</td>
</tr>
<tr>
<td>C</td>
<td>Right</td>
<td>33</td>
<td>Male</td>
<td>55</td>
<td>165</td>
</tr>
<tr>
<td>D</td>
<td>Right</td>
<td>23</td>
<td>Male</td>
<td>90</td>
<td>175</td>
</tr>
<tr>
<td>E</td>
<td>Right</td>
<td>22</td>
<td>Male</td>
<td>90</td>
<td>174</td>
</tr>
<tr>
<td>F</td>
<td>Right</td>
<td>23</td>
<td>Male</td>
<td>49</td>
<td>162</td>
</tr>
</tbody>
</table>

Fig. 7. Torque control of the MRB under the variation of the rotational speed (Reference torque: 5Nm)

Fig. 8. Connection from MRB to pedal shaft

Fig. 9. Experimental setup for sensory evaluation and view of display

Fig. 10. Reference torque of the brake in the experiment
The pedal torque was controlled by the MRB. By switching the reference torque of the brake depending on the rotational angle of the crank, we can apply the different torque (reaction force) on the left and right pedal. For every subject, we conducted two types of tests. In the first sets of tests, we defined their right feet as the tested feet, and their left feet as the reference feet. In the next sets of tests, the role of each foot was exchanged. Figure 10 shows a sample of the reference torque in the experiment. The upper view of the figure shows the reaction force on the tested foot and the reference foot. The lower view of the figure shows the change of the reference torque of the MRB corresponding to the upper sample profiles. At the start of the test, both of the reaction forces are same. Only the reaction force on the tested foot is gradually increased by a constant increment (ascent phase). If a subject feels a difference between the reaction forces on the both feet, he presses the click switch attached on the handle (Fig. 9). At the same time, the control process changes from the ascent phase to the descent phase. In the descent phase, the reaction force on the tested foot is gradually decreased. In the next stage, if the subject feels a difference between both of the reaction forces, he releases the switch. At the same time, the control process changes from the descent phase to the ascent phase.

The experimental conditions are shown in the table III. We selected 3 different reaction forces for the initial torque (standard stimulus). This means we conducted totally 6 trials for every subject. Every trial continued till the number of the on-off of the switch reaches 20. We instructed that they rotate the pedal at less than 3.0 rad/s by their efforts with watching the monitor (Fig. 9).

Points of subjective equality (PSE) are calculated as the averages of the torques at the moment when the switch is turned on and off. Difference thresholds (DL) are calculated as a half value of the average of the difference between torques at the moment when the switch is turned on and off.

### C. Result

Experimental results for the 3 different standard stimuli are listed in the table IV, V, and VI. Almost of the all results are available. However, the PSE and DL of the right foot of the subject B in the case of 5 Nm standard stimuli were not measurable. In the discussion section below, we calculated the averages and the standard deviations by eliminating these unavailable data.

### D. Discussion

Constant errors (CE) are calculated by subtracting the standard stimuli (ST) from the PSEs. The Fig. 11 shows the relationship between the STs and CEs. The CEs tends to decrease with the increase of the ST. However, there is no significant difference according to T-tests.
The Fig. 12 shows the relationship between the STs and DLs. The DLs tend to increase with the increase of the STs. However, there is no significant difference according to T-tests. For healthy males, the DL is 1 ~ 2 Nm in this range of ST. This value indicates the required accuracy for the torque generator of the VR Bike.

According to the experimental results for healthy young male subjects, the perceptual ability of their feet and legs are not so high, and its DL is about 1.5 Nm. It is thought that the DLs of the elderly and the disabled are higher than this result, because some of them have perception disorders. With respect to the difference of gender, it is not clear how much difference exists. We should conduct additional tests for female subjects.

The cylindrical MRB can control its braking torque with the accuracy of less than 0.5 Nm, when the speed compensation was used. This value is smaller than the DLs of the subjects in this paper. This fact implies that the MRB is an available component as the torque generator of the VR Bike.

IV. CONCLUSION

In this paper, we discussed torque control method of the cylindrical MRB. We developed the VR Bike by attaching the cylindrical MRB and controlled the pedal reaction force. Sensory evaluation tests of healthy young male subjects were also conducted to find the DLs of the pedal reaction torque as a requirement of the torque accuracy of the brake. According to the experimental results, the DLs are about 1 ~ 2 Nm in 3 different STs (5Nm, 10Nm, and 15Nm) for healthy young males.

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