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# Walking Sensation in Low- and High-Viscosity Fluids Using a Lower-Limb Force-Feedback Exoskeleton with MR Fluid Brake –The Effect of Changes in Visual on Users' Subjective Evaluation–

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*Abstract*— **In recent years, various haptic devices have been used to reproduce the senses of touch and force when interacting with virtual fluids. This study focuses on reproducing the resistance force experienced during underwater walking movements in a virtual reality (VR) space using a lower-limb force-feedback exoskeleton. To realize disaster simulations with a greater sense of fear and realism for the user, we focused on the necessity of parameter design based on human subjective evaluation when constructing a force-feedback model for the sensation of underwater motion. This study aims to clarify the influence of visual viscosity information on the user's subjective evaluation. Based on the drag model and the added mass force model proposed in previous research, we constructed a composite model in which the contribution ratio of both can be varied. It is conducted an evaluation experiment by combining two types of fluid visuals with different viscosities and four force-feedback conditions. The analysis revealed that visual viscosity information affects the criteria for judging the sensation of viscosity and the way force feedback is perceived. Furthermore, it became clear that as the viscosity changes, the correlation structure among the subjective evaluation items also changes.**

## I. INTRODUCTION

In recent years, the impact of global climate change has become more severe, and the frequency of natural disasters is increasing worldwide [1]. To minimize human casualties, it is important to simulate actions during a disaster beforehand to understand the risks. Recently, disaster prevention drills assuming flood damage have been conducted using virtual reality (VR) technology [2, 3]. However, these drills are primarily visual experiences, and it is necessary to reproduce physical sensations and resistance to provide a more realistic disaster experience.

Existing research has reproduced tactile and force-feedback interactions with virtual fluids in VR spaces using haptic devices. Examples include presenting the sensation of inertia by changing a device's weight or center of gravity [4–7], reproducing skin sensations with air jets [8], presenting temperature and texture with masks or gloves [9, 10], and reproducing fluid resistance with a finger exoskeleton [11]. However, these target the face and hands, and the reproduction of walking resistance applied to the lower limbs is insufficient. As these devices target the face and hands, an approach for the lower limbs is crucial to simulate the difficulty of movement in an actual flood disaster.

As examples of force feedback for the lower limbs, there is the Propel Walker [12], which uses fan propulsion to present buoyancy and resistance, and Ground Flow [13], which uses actual water. However, there are no examples that reproduce the joint resistance associated with walking movements. The authors have previously used a lower-limb exoskeleton device to present a sensation of underwater motion inspired by the drag and added mass forces that occur in water [14, 15]. However, the motion was primarily performed while seated, and force-feedback during walking was not provided. Additionally, when considering actual disaster simulations, it is necessary to construct a force-feedback model that takes into account the influence of psychological factors, such as fear, on human motor perception.

In this study, for constructing a force-feedback model for the sensation of underwater motion, an approach is taken of designing parameters based on human subjective evaluation, rather than pursuing only the reproduction of physical parameters. Through this, our study aims to realize a disaster simulation with a greater sense of fear and realism for the user.

Therefore, this study aims to improve the sensation of walking in a fluid within a VR space using a lower-limb exoskeleton device [14, 15], by investigating the influence of visual fluid viscosity information from an HMD on the user's subjective evaluation of force feedback. In the experiment, two types of visuals with different viscosities with four types of force-feedback models are combined, and evaluations are obtained through a questionnaire. Furthermore, previous research in the VR field has reported changes in force perception due to differences in visual information [16, 17] and a discrepancy between the presented force feedback and the actually perceived force feedback accompanying changes in the viscosity of a virtual fluid [11]. Based on this, clarify the relationship between various subjective evaluation items as viscosity changes, and the influence of visual viscosity on the criteria for judging the sensation of viscosity and the way force feedback is perceived. From these results, we discuss differences in the perceptual system due to changes in viscosity.

The structure of this paper is as follows. Section 2 defines the underwater motion model applied in this study, Section 3 describes the lower-limb force feedback exoskeleton device and system overview. Section 4 describes the virtual fluid walking experiment to verify the effect of visual viscosity

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Figure 1. Overview of a lower limb force feedback exoskeleton.

information on users' subjective evaluations. Finally, Section 5 presents the conclusion and future outlook.

## II. UNDERWATER MOTION MODEL

### A. Modeling in previous study

An object in a fluid is subjected to multiple fluid forces such as drag, added mass force, and buoyancy [18]. However, the sensation of resistance in actual water is complex, and a precise simulation based on physical laws is difficult. Therefore, a previous study [15] focused on drag force, which depends on the object's velocity, and added mass force, which depends on its acceleration, among the fluid forces acting on an object in a fluid when constructing the model.

Drag depends on the relative velocity of the object with respect to the fluid. In the previous study, a force-feedback model for drag was constructed that applies a load torque proportional to the square of the joint angular velocity to the lower limb. Let $\dot{\theta}$ [deg/s] be the angular velocity of the lower limb joint and $k_d$ be the proportionality constant. The mathematical model for the force feedback is as follows:

$$\tau = k_d \dot{\theta}^2 \tag{1}$$

On the other hand, added mass force is an inertial force that arises when the surrounding fluid is also accelerated as an object is accelerated, and it increases in proportion to the acceleration. In the previous study, a force-feedback model for the added mass force was constructed that applies a load torque proportional to the joint angular acceleration to the lower limb. Let $\ddot{\theta}$ [deg/s$^2$] be the angular acceleration of the lower limb joint and $k_a$ be the proportionality constant. The force-feedback torque τ for the added mass force is given by the following equation:

$$\tau = k_a \ddot{\theta} \tag{2}$$

### B. Composite Model

A previous study [15] verified the effectiveness of the above two force-feedback models for the kinesthetic sensation of swinging the right leg in a virtual underwater environment. The results showed that the added mass force model surpassed the drag model in scores for the user's sense of presence and reality. However, the study was limited to force feedback for only the knee joint in a seated posture, and since only one type of visual was presented, the effect of changes in visual information on the user's subjective evaluation of force feedback was not verified.

As mentioned earlier, the added mass force depends on the amount of surrounding fluid that accelerates with the object's motion, but the range of the motion's influence changes with the fluid's viscosity. However, since it is difficult to accurately simulate this range of influence, existing research calculates the added mass force for basic shapes assuming an inviscid fluid [19]. On the other hand, because actual fluids have viscosity, it is thought that the contributions of drag and added mass forces changes with differences in visual viscosity information. Therefore, in this study, it is used the following composite model that combines drag and added mass force as the force-feedback torque:

$$\tau = \alpha k_a \ddot{\theta} + (1 - \alpha) k_d \dot{\theta}^2 \tag{3}$$

Here, $\alpha$ is a weighting coefficient that indicates the contribution ratio of drag force and added mass force. In the experiment, four conditions of force-feedback were presented by varying $\alpha$ for two types of fluid visuals with different viscosities, and verify how differences in visual viscosity information affect the user's evaluation tendencies and their criteria for judging the sensation of viscosity.

## III. LOWER LIMB FORCE FEEDBACK EXOSKELETON

### A. Overall Structure

The lower-limb exoskeleton device used in this study is shown in Fig. 1. This device is a partially improved version of a previous model [14] and consists of joint units placed at the hip and knee joints and link parts. The joint unit is composed of a Magnetorheological (MR) fluid brake (MRB, hollow type, ER tec Co.) and a rotary encoder (E6A2-CW3C 500P/R 0.5M, OMRON Corp.). The weight of the device is approximately 5.6 kg. Cuffs and belts for securing the device to the leg are connected to the links, transmitting the output torque from the joint units to the entire leg.

The MRB can output brake torque by applying a magnetic field via an electric current. The MRB used in this study has a high-power density with a maximum output torque of about 7 Nm and a fast response time of about 10 ms [20]. Also, its light weight of approximately 320 g makes it suitable for integration into wearable devices. In this device, the MRBs placed at each joint output brake torque in the direction opposite to the joint's movement, thereby presenting the resistance force during fluid walking. Each joint can be controlled independently, and any desired torque can be output by a command signal. In the subsequent experiments, based on the angle data from the encoders attached to the joint units, a resistance force corresponding to equation (3), which combines drag and added mass force, is output.

There are three main improvements from the previous model. The first is the weight reduction of the device by changing the material of each part, the second is the

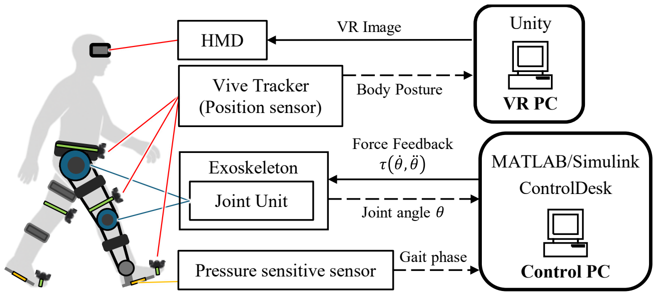
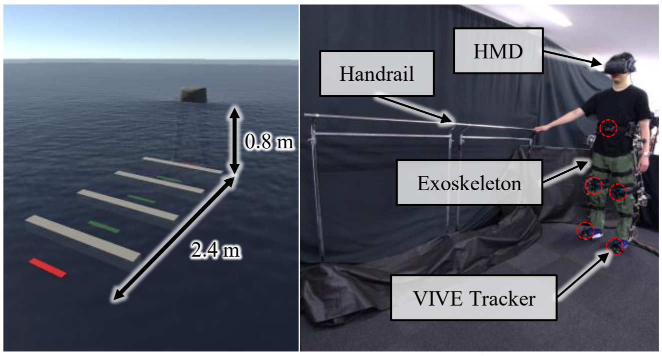


Figure 2. VR rendering system and control system for lower-limb force feedback exoskeleton device.



(a) (b)

Figure 3. Experimental environment for virtual fluid walking experiment: (a) VR fluid image (b) Real environment walking space.

improvement of wearing comfort by changing the shape of the cuff part, and the third is the increase in the degree of freedom in the internal/external rotation direction of each joint by using ball joints. These changes have reduced the discomfort of the device that occurs during walking. Also, while the previous model could amplify the brake torque output by the MRB with the rotation of the axis using a planetary gear reducer; however, this had the disadvantage of also amplifying the torque when no current was applied to the MRB. In this study, to minimize this unapplied resistance, the gear ratio is set to 1:1 and it is operated without amplification.

### B. *System Configuration*

A simplified diagram of the system configuration of this device is shown in Fig. 2. The system consists of a user, a PC for VR video rendering, and a PC for control. The rendering PC acquires the user's posture from a VIVE Tracker (VIVE Tracker 3.0, HTC Corporation) attached to the body and the HMD (VIVE Pro 2, HTC Corporation) itself. The rendering PC then uses 3D computer graphics (3DCG) software (Unity 6000.0.51f1) to render VR video synchronized with the body's movements in the real world. Command signals to the device are output as voltage from ControlDesk (dSPACE Corporation) via a program on MATLAB/Simulink (ver2015a, The MathWorks, Inc.). The output voltage is converted to current by a motor driver (JW-143-2, Okatech Co., Ltd.) and applied to an MRB. The walking phase is identified by a pressure sensor (MF02-N-221-A01, TAIWAN ALPHA ELECTRONIC CO., LTD) attached to the sole of the foot.

## IV. VIRTUAL FLUID WALKING EXPERIMENT

The purpose of this experiment is to verify the effect of visual fluid viscosity information on the user's subjective evaluation of force feedback in the force-feedback model proposed in equation (3).

### A. *VR Environment*

The VR content presented to the subjects is shown in Fig. 3(a). A model of the lower body from the waist down, created with modeling software (Blender 4.4), was placed in the VR space. This model was synchronized with the actual leg movements, visualizing the user's own lower-body movements to ensure safety. The subjects experienced walking in a fluid with a water level set to 0.8 m in the VR space. The "Interactive Water V2" [21] water shader for VR was used to reproduce the texture of the water surface. This shader can draw the spread of ripples centered on the location where the foot touches the water. Subjects started from a red line and walked at their own pace, using green lines placed at 0.6 m intervals as a guide. At this time, to encourage them to lift their feet higher than in normal walking, they were asked to step over a translucent block (20 cm high) located between the lines. One trial consisted of starting with the right foot and continuing until both feet were aligned on the fourth red line, with three trials conducted for each condition.

### B. *Experimental Environment*

The experimental environment in the real world is shown in Fig. 3(b). A sufficient walking space was secured for the VR play area. A 1 m high handrail was provided on the subject's right side to prevent loss of balance while walking with the exoskeleton device. The subjects wore an HMD on their head and a total of five VIVE Trackers: one on the tip of each foot, one on each knee, and one on the abdomen.

### C. *Conditions*

#### 1) *Visual Condition*

Two types of visual conditions were set: a low-viscosity and a high-viscosity liquid. Fig. 3(a) shows an example of the low-viscosity condition. In this study, to generate water surface waves in real time, a simulation shader based on the wave equation using Custom Render Texture was used. The visual texture was changed by adjusting the fluid's color, reflectivity, and glossiness, while the physical difference in viscosity accompanying walking was expressed by switching the wave speed and damping coefficient. As a result, the low-viscosity fluid had a high wave speed and low damping, while the high-viscosity fluid had a low wave speed and high damping, reproducing the difference in viscosity in terms of both appearance and movement.

#### 2) *Force Feedback Condition*

In equation (3), four conditions (Conditions 1–4) were randomly presented to the subjects by varying the parameter $\alpha$, which determines the respective ratios of added mass force and drag force ($\alpha = 1, 0.67, 0.33, 0$). At this time, the coefficients $k_a$, and $k_d$ were set to $k_a = 0.02$, $k_d = 0.001$ so that the maximum torque at the knee joint would be approximately the same for each condition. When $\alpha = 0.67$ or 0.33, there is a possibility that the phase difference between the added mass force and the drag force could cause them to

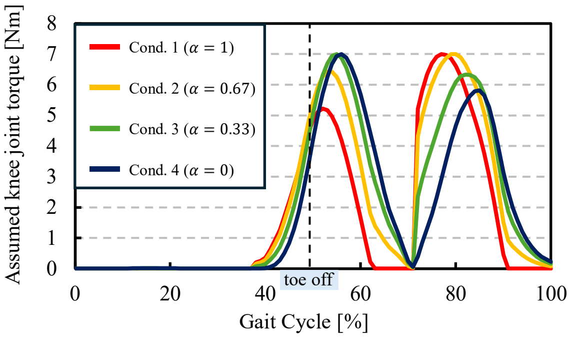


Figure 4. Assumed torque applied to the right knee joint.

TABLE I. QUESTIONNAIRE ITEMS

| | |
|---|---|
| Q1 | How did you feel about the fluid you experienced? |
| | 0 : thin, 100 : thick |
| Q2 | In Q1, what information did you mainly use to judge the " viscous sensation"? |
| | 1: completely visual, 2: almost visual, 3: somewhat visual, 4: 50-50 visual and force,<br>5: somewhat force, 6: almost force, 7: completely force |
| Q3 | How strong was the resistance you felt in your legs? |
| | 0: Didn't feel it at all, 100: Felt it very strongly |
| Q4 | Did you feel like you were walking in the fluid shown in the visual? |
| | 0: Didn't feel it at all, 100: Felt it very strongly |
| Q5 | How closely did the visual and force sensations match? |
| | 0: No match at all, 100: Perfect match |

cancel each other out, reducing the absolute value of the output torque. Therefore, in this study, the force-feedback torque was calculated using the following equation, which weights the absolute value of each component.

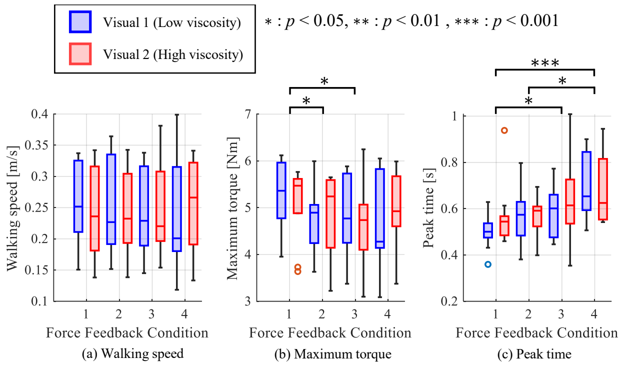
$$\tau = \alpha k_a\left|\ddot{\theta}\right| + (1-\alpha)k_d\dot{\theta}^2 \tag{4}$$

Fig. 4 shows the time-series waveform of the expected command torque to the right knee joint, calculated based on walking data obtained in advance while wearing the exoskeleton device. The walking cycle is defined as one period from when the right foot makes contact with the ground until the next time the right foot makes contact. From Fig. 4, since the peak of resistance for angular acceleration occurs earlier than for angular velocity, it is expected that for $\alpha = 1$ (added mass force only), resistance will occur at the start of movement, and for $\alpha = 0$ (drag force only), torque will be output at the peak of movement speed. The maximum torque during walking depends on the joint's angular velocity and acceleration, but it is approximately 7 Nm at the knee and 3 Nm at the hip.

### D. Procedure

An experiment was conducted on nine adult males (age: 22.3 ± 0.87 years, height: 170.3 ± 4.90 cm, weight: 55.2 ± 4.92 kg) for each force feedback condition according to the following procedure.

- After receiving an explanation of the experiment, the subject puts on the exoskeleton device, HMD, and VIVE Trackers, and stands on the red line in the VR space.



(a) Walking speed (b) Maximum torque (c) Peak time

Figure 5. Relationship between Force Feedback Conditions and (a) Walking speed, (b) Maximum torque, and (c) Peak time.

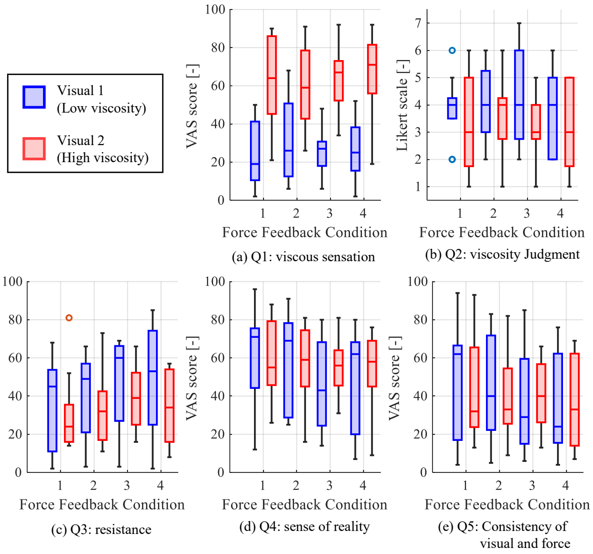
- The subject begins walking with the right foot, and finally aligns both feet on the fourth red line.
- After returning to the starting point again and performing the above action a total of three times, the subject answers the questionnaire described later.

The subjects first experienced the four force-feedback conditions randomly under the low-viscosity visual condition, and then experienced the same four force-feedback conditions randomly under the high-viscosity visual condition. This research has been approved by the Research Ethics Committee for Human Subjects at Chuo University [Control Number: 2024-024(2)].

### E. Evaluation Method

Table 1 shows the questionnaire items. Visual Analog Scale (VAS) from 0–100 was used for Q1, Q3, Q4, and Q5, while a 7-point Likert scale was used for Q2. Q1 asks the subject to imagine the viscosity of "water" they encounter daily and to rate how the viscosity of the experienced fluid felt in comparison. Q2 asks whether they prioritized visual or force information when judging the sense of viscosity. Q3 asks for the strength of the resistance compared to the subject's imagined force evoked by the presented visual. That is, when the felt resistance was comparable to the subject's imagined force from the visual, the score would be around the middle value of 50. Q4 asks about the realism of the VR experience, and Q5 asks about the degree of consistency between the presented visual and the force feedback.

As evaluation methods other than the questionnaire, walking speed, maximum torque during the swing phase (corresponding to the peak in the latter half of the walking cycle in Fig. 4, during which the knee joint is extending), and the peak time from when the maximum flexion angle is reached. This peak was focused on because visually, water ripples are generated at this timing, and resistance is more easily felt during knee extension. For these three items and the questionnaire results, a 2-way ANOVA using Aligned Rank Transform (ART) (significance level 5%) was performed to verify the main effects and interaction of the visual and force-feedback conditions.



(a) Q1: viscous sensation (b) Q2: viscosity Judgment (c) Q3: resistance (d) Q4: sense of reality (e) Q5: Consistency of visual and force

Figure 6. Questionnaire results (Q1, Q3, Q4, and Q5: VAS scores; Q2: Likert scale).

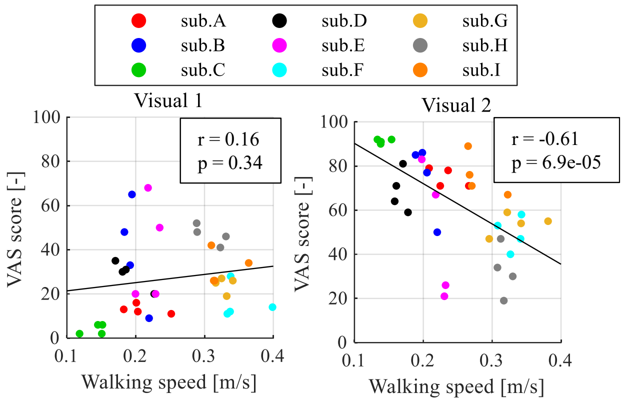


Figure 7. Relationship between walking speed and Q1(sense of viscosity).

### *F. Results and Discussions*

#### *1) Walking speed, peak torque, peak time*

Fig. 5 shows (a) walking speed, (b) maximum torque during the swing phase, and (c) peak time from reaching the maximum flexion angle. For walking speed, neither the main effects of the visual condition and force feedback condition nor their interaction were significant. We speculate this is because walking speed was not controlled in this experiment, leading to large individual differences in the subjects' movement.

For maximum torque and peak time, the force-feedback condition was significant as a main effect. The visual condition as a main effect and the interaction were not significant. A post-hoc test (Tukey's honestly significant difference test) on the force-feedback condition showed that for maximum torque, there were significant differences between condition 1–2 ($p = 0.0428$) and condition 1–3 ($p = 0.0285$). For peak time, significant differences were found between condition 1–3 ($p = 0.0218$), condition 1–4 ($p < 0.0001$), and condition 2–4 ($p = 0.0160$).

However, regarding the maximum torque, it was confirmed from Fig. 5(b) that the overall output torque was smaller than the expected torque shown in Fig. 4. Additionally, in visual 1, the median value tended to decrease as $\alpha$ decreased, which is consistent with the change in $\alpha$ in equation (3). Furthermore, because the peak time depends on $\alpha$ according to equation (3), it is thought to have been less affected by inter-subject variability than the maximum torque. Furthermore, although peak time depends on $\alpha$ as per equation (3), it is considered that it was less affected by individual subject variability than the maximum torque.

#### *2) Each subject's discussion*

Fig. 6 shows the questionnaire results for each force-feedback condition. For Q1, the main effect of the visual condition was significant ($p < 0.0001$). However, the force-feedback condition for Q1 and the interaction between the visual and force-feedback conditions were not significant. For Q2 through Q5, none were significant. To analyze the data in more detail, it is calculated the correlation coefficients between the subjective evaluation items. For visual 1, positive correlations were found between Q1 and Q2, Q1 and Q3, and Q4 and Q5 (Q1–Q2: $r = 0.66$, $p < 0.0001$; Q1–Q3: $r = 0.52$, $p = 0.0011$; Q4–Q5: $r = 0.79$, $p < 0.0001$). For visual 2, positive correlations were found between Q2 and Q3, Q2 and Q5, and Q3 and Q5 (Q2–Q3: $r = 0.74$, $p < 0.0001$; Q2–Q5: $r = 0.75$, $p < 0.0001$; Q3–Q5: $r = 0.74$, $p < 0.0001$). Furthermore, when we calculated the correlation coefficients between the three items in Fig. 5 and the subjective evaluation items, only walking speed and Q1 for visual 2 showed a negative correlation ($r = -0.61$, $p < 0.0001$) (Fig. 7).

The significant main effect of the visual condition on Q1 (sense of viscosity) indicates that vision had a large influence on the sensation of viscosity. One factor for this is considered to be the effect of walking speed. Fig. 7 shows the VAS scores for Q1 against walking speed. As seen in Fig. 7, especially for visual 2, the viscosity score decreased for subjects with a faster walking speed. This is thought to be because while in a real high-viscosity fluid, translational resistance increases with walking speed, in this experiment, resistance is reproduced only by torque at the joints. This discrepancy with reality may have caused a decrease in the perceived viscosity. On the other hand, in visual 1, when the sense of viscosity was high, there was a tendency to use force feedback as the basis for judgment and also to perceive a greater sense of resistance. This suggests that when visual viscosity is low, the influence of force feedback may become stronger.

Furthermore, in visual 2, when vision was used as the criterion for judgment, there was a tendency for the sense of resistance to be low and for the congruence between visuals and force feedback to decrease. It is considered this is because the output torque was smaller than expected, and the torque transmitted from the device was insufficient compared to the force feedback anticipated from the visual information of a high-viscosity fluid. Therefore, for presenting force feedback that simulates a high-viscosity fluid, It is thought it is necessary to increase the resistance force by increasing $k_a$, and $k_d$ in equation (3) and by applying torque to the hip joint.

From these results, it was confirmed that in force feedback for walking in a fluid, the user's criteria for judging the sensation of viscosity and the way they perceive force feedback change with variations in visual viscosity information. To realize a disaster simulation with a greater sense of fear and realism for the user, it is necessary to take an approach of designing the parameters of the force-feedback model based on such differences in evaluation criteria that accompany changes in viscosity. Also, all subjects in this experiment were in the same age group, and the number of subjects was limited to nine. Therefore, in the future, it is necessary to verify generalization by increasing the age range and number of subjects, as well as constructing an experimental environment that simulates a disaster setting.

## V. CONCLUSION

In this study, it is investigated the effect of visual viscosity information on users' subjective evaluation of force feedback for walking in a fluid in a VR space. Based on the drag model and the added mass force model proposed in previous research [14], it is constructed a composite model in which the contribution ratio of both can be arbitrarily set. In the experiment, four force feedback conditions were set by changing this contribution ratio for two types of fluid visuals with different viscosities. The results of the experiment confirmed differences in force perception and the imagined force feedback for the visuals due to changes in visual viscosity.

In the future, we aim to expand the variations of visuals and movements and design a personalizable force-feedback model that reflects the knowledge gained in this study, thereby aiming for applications in VR disaster simulations that can achieve a higher sense of realism and immersion.

## ACKNOWLEDGMENT

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