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Effect of Force Feedback during Interaction with Straight-line Movement in a VR Space by an Upper-limb Wearable Force Feedback Device

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***Abstract*—The authors developed an upper-limb-mounted force feedback device using pneumatic artificial muscles and a magnetorheological fluid brake. This force feedback device utilizes a magnetorheological fluid brake and incorporates a mechanism with bevel teeth in the shoulder, providing a wide range of motion. In previous studies, it was confirmed that the device can simulate friction with virtual objects in a virtual reality (VR) space. In this study, the authors conducted force feedback experiments using the developed device in VR content, including linear walking, to examine the influence on motion sickness and immersion. The conditions included the presence or absence of the force feedback device and different methods of movement, such as walking, visual movement, and controller-based movement. Participants were surveyed to evaluate their experiences under these conditions. The results indicated that, concerning motion sickness, the method of movement had a more significant influence than the presence or absence of force feedback. Additionally, for immersion, force feedback, particularly including walking movements, had the greatest potential to enhance the sense of immersion.**

I. Introduction

A head-mounted display (HMD) enables users to immerse themselves in a virtual reality (VR) space, allowing them to perceive various virtual objects visually while moving around a room. However, an HMD alone does not provide a sense of force in the VR space as it does in the real space. Force feedback devices (FFDs) have attracted significant attention to express this sense of force. Common FFDs include tabletop FFDs [1,2]. These devices have the advantage that the user is not burdened by the weight of the device because it is fixed to a desk. However, they have the disadvantage that the user's range of movement is limited. However, a wearable FFD that allows users to move has been developed [3-5]. This device enables a wide range of operation in a virtual space with the same behavior as that of a human being, eliminating the need for the user to be conscious of the controller operation for movement and improving the sense of immersion. In addition, if the same movement in the real space as in the VR space is possible, the acceleration estimated from the visual information and the acceleration received from the inner ear, such as the semicircular canals and otoliths, will match, and the sensory discrepancy [6] proposed as a cause of motion sickness can be expected to be suppressed.

However, mounted devices generally utilize both a motor and a reduction gear to generate the necessary torque for force feedback. This results in an increased device weight owing to the use of the reduction gear. Additionally, safety concerns arise, including the potential for harm to the wearer owing to motor malfunctions, given that a motor is an active actuator. On the other hand, FFDs employing pneumatic rubber artificial muscles have been developed as alternatives to motors [7-9]. These devices can provide a natural elastic force owing to the structural elasticity of artificial muscles. However, the slow response speed of pneumatic drives makes it challenging to simulate friction and viscosity. FFDs utilizing electrorheological and magnetorheological (MR) fluid brakes, which utilize functional fluids, have also been developed [10-12]. These devices adopt passive force feedback methods to ensure mechanical safety. Moreover, they offer continuous torque control with a rapid response, enabling the simulation of friction and viscosity. However, force feedback methods using brakes cannot accurately represent elasticity, such as that of a compressed spring pushing back.

To solve these problems, we proposed FFDs that passively control joint stiffness by combining lightweight, high-power pneumatic artificial muscles and MR fluid brakes. We developed a wearable four-degrees-of-freedom (DOF) FFD [12], an upper-limb bimanual FFD [13], and a bevel-tooth-embedded FFD [14], and concluded that the elastic, viscous, and frictional forces of a virtual object can be presented through rigidity presentation experiments of the four-DOF FFD [13]. However, according to the results of a questionnaire, the weight of the device affects the sensibility evaluation, and the subject's physical burden needs to be reduced. Therefore, in a previous study, the prototype of a new FFD was presented and basic characteristic tests were conducted to reduce the physical burden on subjects [12]. Other existing studies have conducted force feedback experiments using a movable wearable device [15]; however, they did not sensitively evaluate the effects of different ways of moving in the real space. To demonstrate the effectiveness of the ability to move a wearable device, which is not present in tabletop devices, the quantitative verification of the effect of the VR content involving movement is necessary.

Therefore, this study aimed to verify the effect of the combination of force sensation presentation and walking movement on human sensation when interacting with virtual objects using a wearable FFD while moving within a VR space. We conducted force presentation experiments on a virtual viscous object, which included movement using the device, and examined the advantages of a wearable device

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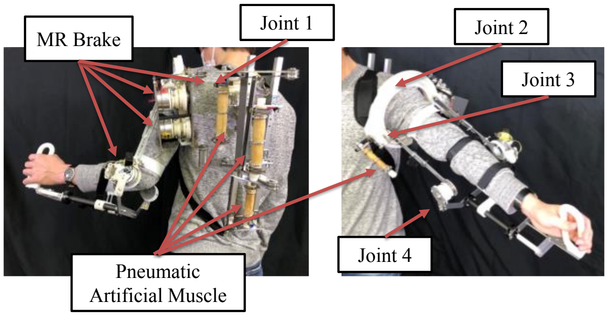


Fig. 1. Bevel-type FFD [12].

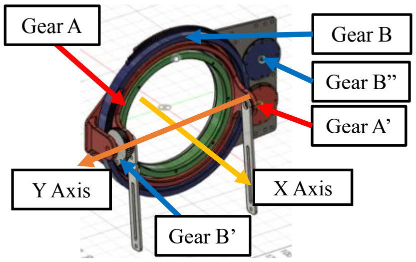


Fig. 2. Shoulder bevel gear mechanism.

TABLE I. CONTENT OF QUESTIONNAIRE FOR SUBJECTS

Parts	Motion	Range [deg]
Shoulder	Flexion	0 ~ 180
	Abduction	30 ~ 170
	Horizontal Flexion	0 ~ 120
	Horizontal Extension	0 ~ 30
Elbow	Flexion	130

that enables wide-area movement from the following two perspectives.

- Reduction of motion sickness by synchronizing visual information with movement and the presentation of force sensation.
- Improved sense of presence through the presentation of force information.

II. BEVEL TOOTH BUILT-IN FORCE FEEDBACK DEVICE

A. Overview

The FFD developed in this study is illustrated in Fig. 1. This device has 4-DOFs (3-DOFs in the shoulder and 1-DOF in the elbow). The MR fluid brake and the artificial muscles were connected to the drive shaft. As people tend to overestimate external forces owing to muscle fatigue [16], it is undesirable for an FFD to place a physical burden on users. Therefore, we considered that, by concentrating the driving components near the torso, the shoulder torque required for operation could be reduced and the burden on the arms could be alleviated. To realize this concept, a new shoulder bevel gear transmission mechanism (Fig. 2) is introduced. This device has 3-DOFs at the shoulders and 1-DOF at the elbows, for a total of 4-DOFs, corresponding to the movements shown in Table I. The arm length of the device is changeable and adjustable to suit the wearer.

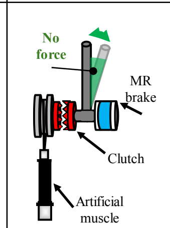
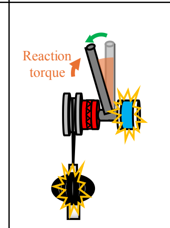
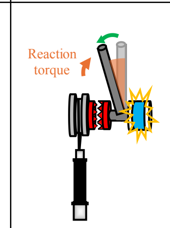
Rendering force	No force	Elasticity	Friction or viscosity
Schematic diagram			
Artificial muscle	No air pressure	Variable stiffness	No air pressure
MR brake	Minimum torque	Variable torque	Variable torque

Fig. 3. System configuration of an FFD.

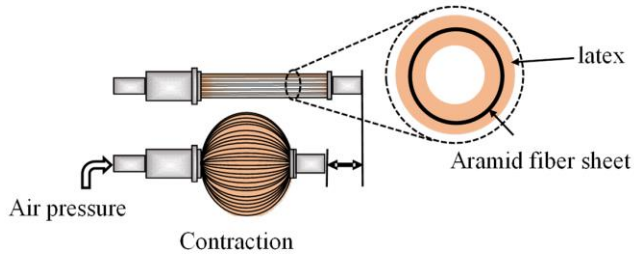


Fig. 4. Construction of an artificial muscle.

B. Shoulder Bevel Gear Transmission Mechanism

This mechanism consists of a double-structured bearing and multiple gears. The gears are rotated around the Y-axis for shoulder abduction and around the X-axis for shoulder flexion. Therefore, this mechanism can provide a sensation of force in the directions of shoulder flexion and abduction. As the weight of the device is applied near the torso by this mechanism, the load received by the arms is reduced by 36% compared with that of the old device [14].

C. Force Feedback Method

Force feedback was provided by controlling the stiffness of each joint using an MR brake, a clutch mechanism, and pneumatic artificial muscles, as shown in Fig. 3. The presence or absence and the type of force feedback were switched by applying air pressure to the artificial muscles and switching the brake torque of the MR brake. The following three force feedback patterns were used: (1) No-load state: No air pressure was applied to the artificial muscles, and no brake torque was applied to the MR brake. (2) Elastic presentation: Air pressure and brake torque were applied to the artificial muscles and MR brake, respectively, according to the target values. (3) Frictional/viscous presentation: No air pressure was applied to the artificial muscles, and the brake torque was applied to the MR brake according to the target value.

D. Axial Fiber-reinforced Artificial Muscle

The structure of the axial fiber-reinforced artificial muscle used in this study [17] is shown in Fig. 4. This artificial muscle is composed of rubber and aramid fibers that expand radially and contract axially when air pressure is applied. Additionally, as the fibers are embedded, a relatively high contractile force can be obtained among the artificial muscles. This artificial muscle is lightweight and has high power density and variable stiffness.

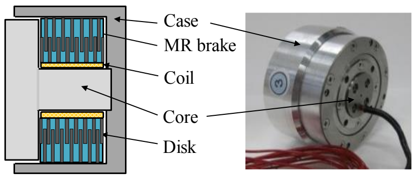


Fig. 5. Construction of the MR brake.

E. Magnetorheological Fluid Brake

A schematic of the MR brake used in this study is shown in Fig. 5. The MR brake comprises an MR fluid, a disk that rotates in conjunction with the inner core, and a coil that generates a magnetic field. When no magnetic field is applied, the MR fluid is a base fluid in which the magnetic particles are dispersed. When a magnetic field is applied, the magnetic particles form a chain of clusters perpendicular to the direction of rotation of the disk. The clusters are broken by the rotation of the disk, and shear stress is exerted as the braking torque.

F. Relationship of Joint Torques and Target Force to the End Effector

The joint torque $\boldsymbol{\tau}$ and end-effector force $\boldsymbol{f}$ of the device can be expressed using the Jacobi matrix $\boldsymbol{J}$ as follows.

$$\boldsymbol{\tau} = \boldsymbol{J}^T \boldsymbol{f} \tag{1}$$

This relationship is used to calculate the joint torque required to provide the target end-effector force (elastic, frictional, or viscous).

The relationship between joint rigidity $\boldsymbol{K_j}$ and end-effector rigidity $\boldsymbol{K}$ can be expressed by the following equation:

$$\boldsymbol{K_j} = \boldsymbol{J}^T \boldsymbol{K} \boldsymbol{J} \tag{2}$$

When friction is applied to the end effector, considering that the presented frictional force is $\boldsymbol{f}_f$ from (1), the torque $\boldsymbol{\tau}_f$ required at the joint has the following relationship.

$$\boldsymbol{\tau}_f = \boldsymbol{J}^T \boldsymbol{f}_f \tag{3}$$

When a viscous force is applied to an end effector, the viscous force $\boldsymbol{f}_v$ can be expressed as follows, with the presented viscosity coefficient $\boldsymbol{C}_v$ and end-effector velocity $\boldsymbol{v}$.

$$\boldsymbol{f}_v = \boldsymbol{C}_v \boldsymbol{v} \tag{4}$$

From (1) and (4), the torque required at the joint can be expressed as

$$\boldsymbol{\tau}_v = \boldsymbol{J}^T \boldsymbol{C}_v \boldsymbol{v}. \tag{5}$$

Each actuator was controlled such that the target torque was the output of each drive axis.

G. Force Feedback System

The force feedback system used in this study is shown in Fig. 6. The system consists of a VR space presentation system and an FFD control system. First, for the VR space system, the user wears an FFD and HMD for VR space presentation, and a tracker is attached to the end-effector force. The VR images are rendered using the game engine Unity on a PC used to build the VR space. Next, the FFD control system uses a dSPACE control board to acquire the joint angles of the device from the encoders of the device joints, and applies the control signals calculated by Simulink to the device to manipulate its joint rigidity. Using the above system, the end effector of the device is presented with the target force feedback.

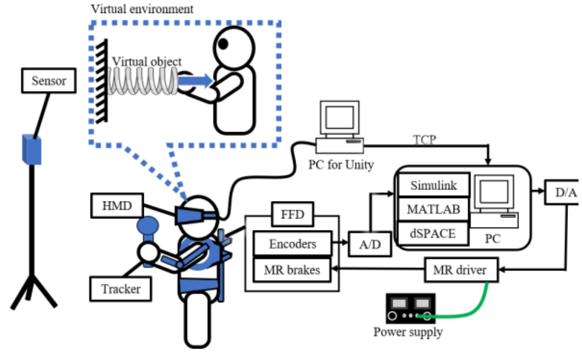


Fig. 6. System configuration of an FFD.

III. Force Feedback Experiments including Straight-line Walking

A. Purpose

This experiment aimed to verify whether force feedback while moving in a VR space is effective in improving the "sense of presence" and reducing "motion sickness." The following is an explanation of the "sense of presence" and "motion sickness," and the expected effects of using a wearable FFD.

The sense of presence is a sensation defined as "the feeling of being there." This sensation depends on the size of the angle of view and is strongly connected to vision, such as being affected by the way the surrounding objects and backgrounds move. However, studies have been conducted on the use of nonvisual stimuli, such as smell and touch, to improve the sense of presence [18,19]. Therefore, we considered that the sense of presence could be improved by presenting reaction forces from virtual objects or force feedback in addition to the visual stimuli obtained by moving within the VR space. In this experiment, we expected a combination of the two types of stimuli to increase the realism of the VR experience.

Next, regarding motion sickness, the cause of motion sickness has not yet been clarified, but the "sensory discrepancy theory" [20] has been proposed as the mechanism that causes motion sickness. This theory states that sickness is induced when sensory information predicted from past experiences does not match actual sensory information. Therefore, we considered that resolving this sensory discrepancy would be an effective means of reducing motion sickness. In this experiment, an FFD reproduced the reaction force from a virtual viscous fluid in the VR space and synchronized the walking of the person wearing the device with their movement in the VR space, thereby reducing the sensory discrepancy. We expect that this will reduce the incidence of motion sickness.

B. Experimental Environment in Real Space

The experimental setup is shown in Fig. 7. The subject wore an HMD (VIVE Pro Eye, HTC) for the VR space presentation and an FFD. As this experiment only presents the viscous force by MR braking, artificial muscles that were not used in the experiment were not mounted. The subject gripped a gimbal-type end effector to move his body.

C. *Experimental Environment in VR Space*

In the VR space constructed on Unity, an object, i.e., a water tank filled with a virtual viscous fluid (Fig. 8 (a)), was placed on the subject's left hand, and another object, i.e., a glove (Fig. 8 (b)), was positioned on the subject's left hand. In this experiment, the glove was used instead of a hand to eliminate the tactile influence of touching the water. Contact judgments were made based on the positional relationship between the glove and the viscous fluid, and ripples were generated on the water surface when the glove touched it (Fig. 8 (c)). In addition, the floor color was changed in the area where the subject walked to clarify the start and end positions of walking.

D. *Experimental Procedure*

The experimental procedure is as follows.

(1) The subjects stood at the position of the start line shown in Fig. 8 (a) and stirred the fluid in the water tank placed in the VR space at an arbitrary timing and an arbitrary number of times in the direction of travel of the subject.

(2) The subject moved toward the goal position in the figure while stirring the fluid in the water tank (Fig. 9). At this time, the subject stopped once before reaching the goal to prepare a section in which the subject was conscious of only the viscous force of the water.

(3) After reaching the goal, the subject returned to the start position.

(4) The water tank was moved toward the goal position again while stirring the water in the tank. This action was not stopped until the goal was reached.

The above procedure was repeated for all the conditions to be implemented.

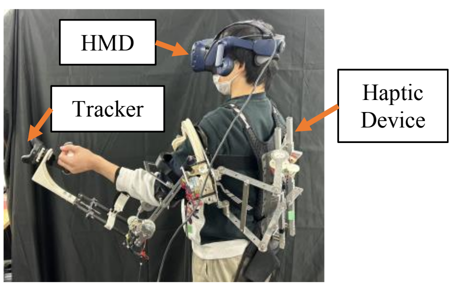
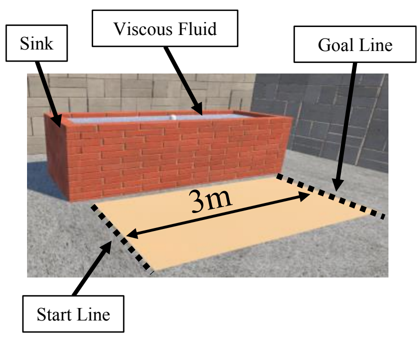
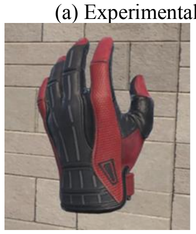


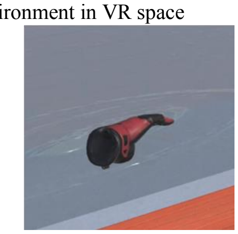
Fig. 7. Subjects wearing the wearable FFD in this experiment.



(a) Experimental environment in VR space



(b) Glove object



(c) Interaction between glove and fluid

Fig. 8. Experimental environment in VR space.

E. *Experimental Conditions*

In this experiment, six conditions were prepared, including two conditions for force feedback and three conditions for the method of movement in the VR space. The two force feedback conditions were "with force feedback (with FFB)" and "without force feedback (without FFB)." In the "with force feedback" condition, the subjects wore the device and were presented with a viscosity of 20 Ns/m while a glove touched a virtual viscous fluid. In the "without force feedback" condition, the subjects performed the experiment without wearing the device. Next, as for the method of movement in the VR space, we conducted three types of experiments: "walk," in which the subject walked; "ON-OFF," in which the subject moved at a constant speed only in the VR space without considering the timing; and "joystick," in which the subject used the VIVE Controller (HTC) like a joystick to move only in the VR space (Fig. 10). The speed of movement in each condition was not standardized. "Joystick movement" is a condition in which the player moves when the controller is tilted in the direction of movement while pulling the trigger of the controller. The movement speed can be controlled by the angle at which the controller is tilted. The subjects were six healthy males.

Fig. 9. Experimental operation.
(Top: VR image Bottom: Moving in real space)

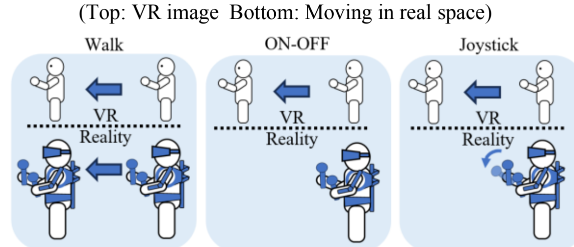


Fig. 10. Conditions for how to move around in the VR space.

TABLE II. CONTENT OF QUESTIONNAIRE FOR SUBJECTS

Q1	Did you feel the water resistance?
Q2	Did you feel intoxicated?
Q3	Did you feel uncomfortable with the experience?
Q4	Did you feel like you were just watching a video?
Q5	Did you feel as if you were actually there?

F. *Evaluation Methods for Force Feedback Experiments including Straight-line Walking*

After each trial, the participants completed a questionnaire consisting of five questions, as listed in Table II. The questionnaire was administered using the visual analog scale (hereinafter referred to as "VAS"), in which a line of a certain length was drawn and the left end of the line was set to "0" and the right end to "strongly agree" (1). The participants were asked to draw a vertical line between 0 and 1 on the VAS to indicate the degree of sensation they experienced during the experiment. The ratio of the length from the left end to the vertical line to the total length of the VAS was used as the VAS score.

IV. Results and Discussion of Force Feedback Experiments including Linear Walking

The average VAS scores of the questionnaire results for Q1–Q5 are shown in Fig. 11 to Fig. 15, respectively.

Q1. Sense of Resistance

There was an evident difference between the "with force feedback" and "without force feedback" conditions, with more subjects perceiving water resistance in the "with FFB" condition. However, it is possible that the subjects experienced water resistance owing to the difficulty in moving their upper limbs when wearing the device. The difference in the perception of resistance in the "with FFB" condition may be due to the fact that the speed of operation was not unified in each condition.

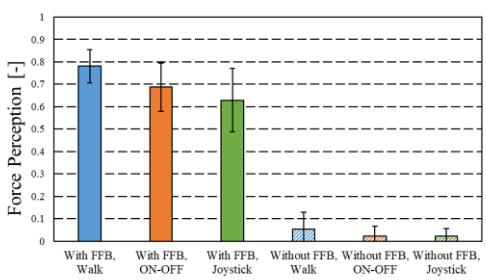


Fig. 11. Average VAS score of force perception (Q1).

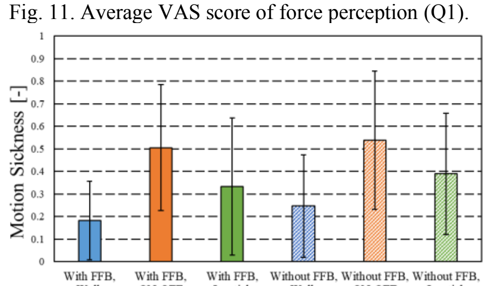


Fig. 12. Average VAS score of motion sickness (Q2).

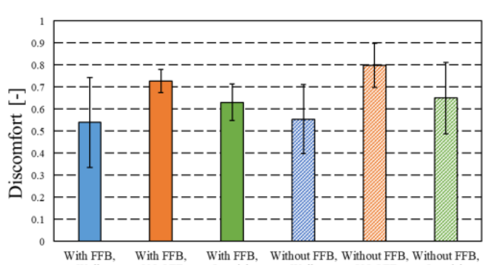


Fig. 13. Average VAS score of discomfort (Q3).

Q2. Motion Sickness

Fig. 12 indicates that the discrepancies in scores between movement methods were greater than those between force feedback conditions, suggesting that VR sickness susceptibility is more influenced by visuals than force sensation. The "walk" condition elicited the least sickness compared to other locomotion methods, likely due to minimal sensory information discrepancies between inferred visual speed and inner ear input. Subjects experienced more intoxication in the "On-Off" condition than in the "joystick" condition, possibly because of the lack of control over timing and speed in "On-Off." Comparing force feedback within the same movement methods, sickness scores were slightly lower with FFB, possibly due to enhanced prediction from experiencing reaction forces when interacting with virtual fluids during walking.

Q3. Discomfort of Experience

Fig. 13 shows that the subject felt the least discomfort in the "walk" condition and the most discomfort in the "On-Off" condition. This is because "On-Off," in which subjects cannot choose the timing of movement themselves, is a movement that is difficult to predict from actual experience, whereas walking movement is the most similar to actual experience, and thus, the subjects felt the least discomfort.

Next, we expected that the presence or absence of the FFB would reduce the sense of discomfort because, when the reaction force from the fluid is expressed by the FFB, it is closer to the real experience. However, when the same movement methods were compared, the differences in scores were generally small, depending on whether force feedback was used. This is due to the high level of abstraction of the word "discomfort," and the influence of tactile FFB factors unrelated to the presence or absence of FFB devices, such as a sense of restraint owing to the wearing of devices and the bias of the center of gravity.

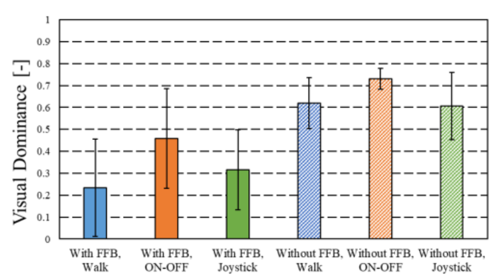


Fig. 14. Average VAS score of visual dominance (Q4).

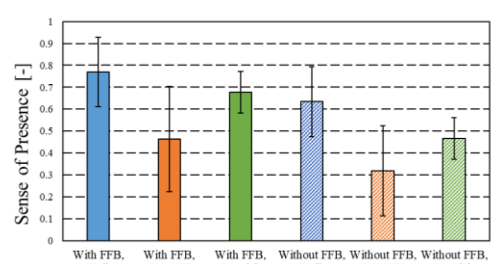


Fig. 15 Average VAS score of sense of presence (Q5).

Q4. Feeling of Just Watching an Image

Fig. 14 shows that the difference in scores between the subjects "with FFB" and "without FFB" is large, and the scores "with FFB" are lower than those "without FFB," suggesting that the subjects were able to perceive the texture of the water more easily with FFB. We believe that this is because the subjects became aware of senses other than sight because the force presented was sufficiently high for them to recognize it, as described in the results of Q1.

Next, comparing the movement methods, the difference in scores between "walk" and "joystick" was small, unlike the response for the discomfort of the experience (Q3), indicating that the discrepancy between sensory information received by vision and the inner ear was not significant. The value for Q4 was the highest for the "On-Off" movement. It is assumed that a situation in which the subject himself cannot choose the timing and speed of movement, that is, a situation in which movement is controlled by another person, leads to a decrease in the sense of movement subjectivity and strengthens the sense of "I felt as if I was simply watching an image."

Q5. Sense of Presence

Fig. 15 shows that the difference in scores between the force feedback conditions was significant, and "with FFB" scored better. To summarize the experimental results, the most desirable score was obtained with the combination of "with FFB" and "walk" conditions. This suggests that FFB should be added to improve the sense of realism, whereas predictable stimuli based on real-life experiences should be added to suppress motion sickness.

V. Conclusion

We conducted force feedback experiments on a wearable 4-DOF FFD, including walking in a straight line, and verified its effects on motion sickness and realism. The results showed that the differences in the method of movement tended to affect the susceptibility to motion sickness more than the presence or absence of force feedback. The motion sickness experienced by the subjects was the lowest in the walking movement condition. Therefore, it is suggested that the interaction in which the subject walks with their feet in the VR space is predictable from the actual experience and is less likely to cause motion sickness. In addition, the VAS score for the sense of presence was the highest when force feedback was combined with walking movements. Therefore, it may be effective to increase the number of force stimuli for a sense of reality to improve the sense of realism. As a future prospect, we will incorporate pneumatic artificial muscles, which were not used in this experiment, into the device and conduct an experiment to determine the elastic force while walking. In addition, we plan to verify the effectiveness of force feedback in VR content, such as in on-the-job training in which participants move while performing complex tasks.

Acknowledgment

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