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Development of a dropping motion presentation device with bellows actuator to improve the sensation of falling in a VR

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Abstract*— This paper describes the improvement of a dropping motion presentation device to enhance the sensation of falling in a VR space. In this study, we developed a bellows actuator-type dropping motion device that is lightweight and bendable in order to improve the sensation of walking when wearing the device. In addition, an exhaust gas control device was fabricated to control the large flow of exhaust air necessary for the bellows actuator to operate, and a two-step dropping motion was realized, which is a motion technique to improve the sensation of falling. In the walking sensation evaluation experiment, the ease of walking when wearing the product and actual walking were evaluated. The results showed that the developed device scored higher than the conventional device in both the subject's subjective sensation and objective evaluation items. There was also a statistically significant difference between these scores, and it was concluded that the improved device contributed to an improvement in the comfort of walking for the wearer.

I. Introduction

Advances in VR technology have enabled a variety of virtual experiences in recent years. In this context, research on haptics technology that provides more realistic sensory feedback by presenting force feedback and tactile sensations has been active. Many of these technologies have already been commercialized as products [1][2][3], but some are still in the research stage or have not yet been fully tested. One of them is the sensation of falling. There are already several examples of presenting the sensation of falling. For example, there is a study [4] on the excitation of the sensation of ascending and descending by presenting vibrations to the sole of the foot, but it was not possible to sufficiently estimate whether the subject was moving upwards or downwards. The fall experience device [5] was developed to raise safety awareness among workers at high altitudes, but its large size and the high degree of physical restraint of the wearer limit its applicability to a wide range of content. Other studies on fall sensation include a study on improving fall sensation using wind [6] and an analysis of the relationship between visual stimuli, posture, and fall sensation [7].

Therefore, this research aims to realize a direct presentation of the sensation of falling by using a shoe-type device. By using a shoe-type device, the user can move freely in the VR space, and the sensation of falling can be presented at the location where the user moves. In a previous study, we proposed and verified the "two-step dropping" method, which presents two short distance drops in reality, one at the start of the drop in the VR space and the other at the landing [8][9]. This concept can reproduce a long-distance fall in VR space with the presentation of a short drop. In addition, the synergistic effect of the visually induced self-motion sensation (vection) caused by the visual information of the VR falling experience and the sense of movement by the force feedback device is expected to increase the sensation of falling [10][11][12]. The specific operation of the device is shown in Fig. 1. This method of presenting dropping motion focuses on the acceleration at start of the fall and the deceleration at landing to simulate the sensation of a long-distance fall. In addition, by changing the pause time between the first and second stages of the drop, it is possible to simulate the sensation of falling for an arbitrary distance in a VR space. The results of a previous study showed that even a fall distance of 75 mm and a fall acceleration of -1120 mm/s^2, which is smaller than the gravitational acceleration in real space, can produce a realistic sensation of falling [8]. In addition, it was shown that deceleration when stopping in the middle of a drop with a deceleration acceleration of 1000 mm/s^2 could reproduce the sensation of a long-distance fall [9].

Continuing this work, the authors are developing a shoe-type device capable of presenting two-step dropping. Examples of shoe-type devices that can operate under the user's weight and move in the direction of gravity include Level-Ups [13], Real Walk [14], and a shoe-type device that uses balloons [15]. However, none of these devices has sufficient speed and stroke performance to present a dropping motion. In addition, a shoe-type device using an MR fluid brake [16][17], which aims to present the sensation of falling, has issues with height recovery after the fall after dropping motion, because it cannot generate active torque. To solve this problem, the authors developed a dropping motion presentation device using an air cylinder [18]. This device is 250 mm long, 140 mm wide, 190 mm high, and weighs 3.6 kg per foot. Also, we conducted an experiment in which subjects were presented with a VR image and a dropping motion, and confirmed that two-step dropping improves the subject's sensation of falling [19]. However, this device was only a prototype, and the size and weight of the device were not fully considered due to the emphasis on the realization of the dropping motion. As a result, it was difficult for the subject to walk while wearing the device, and the advantages of the device as a wearable device with low physical restraint could not be utilized. Therefore, to realize unrestricted movement in VR space and the presentation of the sensation of falling by a wearable device, we considered it necessary to develop a device that places more emphasis on ease of walking.

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This paper presents a newly developed dropping motion presentation device that enables the wearer to walk while wearing the device. The newly developed device is smaller and lighter than previous models by using a bellows-type pneumatic actuator. On the other hand, the bellows-type pneumatic actuator makes it difficult to exhaust air at high speed and pause the exhaust, which are necessary for the two-step dropping presentation concept of this device. We solved this problem by developing a new exhaust control device using a small pneumatic cylinder. In addition, by making the device's wearing part bendable, we aimed to enable natural walking without restricting the dorsiflexion motion of the foot during walking.

The contributions of this paper are as follows.

- A falling sensation presentation device was developed to make it comfortable for the wearer to walk.
- We proposed a method to realize two-step dropping motion in a bellows actuator that requires a large flow rate.
- The comfort of walking was evaluated for the bellows-type dropping motion presentation device that we developed, and it was shown that there was significant difference in the comfort of walking compared to the air cylinder-type dropping motion presentation device that was used in a previous study as a wearable device.

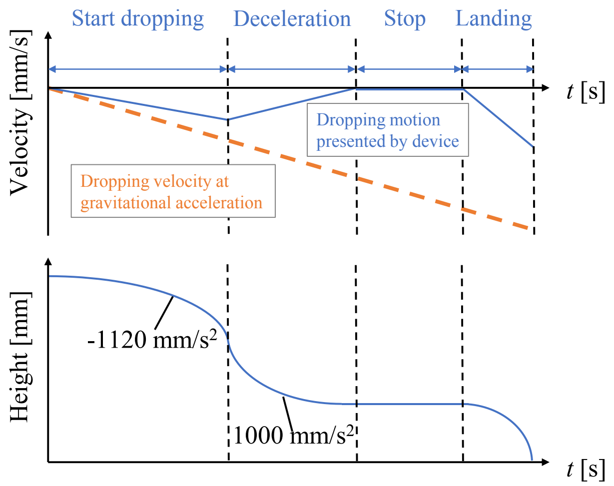

Figure 1. Dropping velocity and ground height from for the drop concept by a force feedback device.

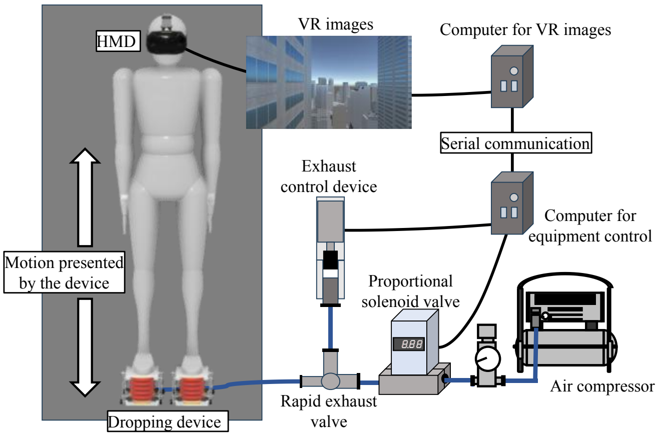

Figure 2. Overview of dropping motion presentation system

The structure of this paper is as follows. chapter 2 introduces the bellows-type falling sensation presentation device and the exhaust control device used to realize the two-step dropping motion. Chapter 3 describes the two-step dropping motion experiment using the bellows-type falling sensation presentation device. In Chapter 4, we conducted an evaluation experiment of the comfort of walking while wearing the bellows-type falling sensation presentation device that we developed, by preparing three types of comparison conditions.

II. Dropping Motion Presentation System

Fig. 2 shows the developed dropping motion presentation system. The system consists of a dropping motion presentation device, an exhaust air control device, a compressor that supplies air to the device, a solenoid valve for pressure control, and a control PC. The dropping motion presentation device moves up and down by actuating a bellows actuator driven by air pressure. An exhaust air control device can control the exhaust air of the dropping motion presentation device. This device enables the two-step dropping motion shown in Fig. 1, which is necessary for falling sensation presentation. The user wears the dropping motion presentation device on his or her feet, and the user can experience a highly realistic falling sensation by receiving the dropping motion presentation in synchronization with the VR image. The user can also walk while wearing the device. Details of each device are shown below.

A. Dropping motion presentation device

Fig. 3 shows an overview of the developed device. The device consists of a bellows actuator, upper and lower plates that sandwich the bellows actuator, and a parallel link mechanism. Air entering through the tube fitting passes through the inside of the plates to the bellows actuator, which extends the actuator. The parallel link mechanism serves to restrain the tilt and limit the stroke of the actuators. The upper and lower plates are made of light-curing resin, which was created using a 3D printer. The link mechanism was made using steel and aluminum parts.

Bellows actuators have a large pressure-receiving area, so the force generated is large even when low pressure is applied. On the other hand, bellows actuators are not suitable for use with high-pressure air, but in the case of the present device, this is not a problem because the necessary output can be secured with an air pressure of about 0.1 MPa. In addition, the height of the actuator is low in the contracted state because the actuator body also contracts, allowing the minimum height of the device to be kept low when it is used as a shoe-type device. In addition, the bellows actuator is lightweight and flexible, making it ideal for use in this device.

Fig. 4 shows an overview of the bellows actuator of this system. The bellows actuator has a two-layer structure. The inner bellows made of silicone rubber has high flexibility and good durability against repeated expansion and contraction. The outer polypropylene bellows has low elasticity and prevents excessive expansion of the inner bellows when air pressure is applied.

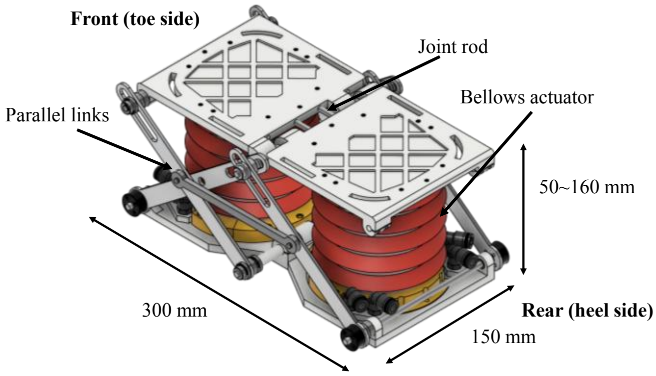

Figure 3. Overview of bellows type dropping motion presentation device

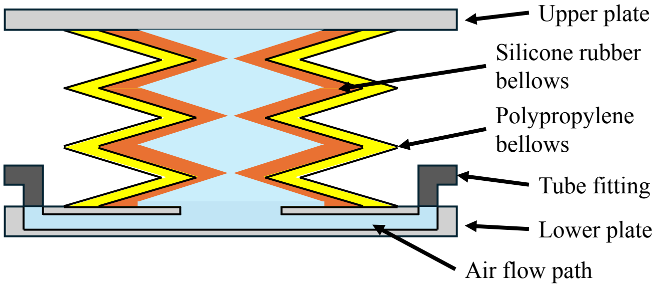

Figure 4. Image of the inside of a bellows actuator

As shown in Fig. 5, the front half of the upper plate is restrained to move parallel to the ground by a link mechanism, while the back half has a degree of freedom in the pitch direction, so that the dorsiflexion motion of the foot during walking is not inhibited. The elasticity of the structure can be adjusted by replacing the connecting rods that connect the front and back of the upper plate with those made of different materials.

The device has a stroke of approximately 110 mm, weighs 2.25 kg per foot, and exerts a lifting force of approximately 600 N when air pressure of 0.1 MPa is applied.

B. *Exhaust control device*

By using a bellows actuator as a dropping motion presentation device, we were able to reduce the weight of the device and ensure its flexibility. However, the bellows actuator requires a large amount of air flow for its operation. There are two ways to increase the exhaust air flow rate, by increasing the number of air supply and exhaust routes or by installing rapid exhaust valves in the air tubes connected to the air supply and exhaust ports. In this study, both methods were employed, and rapid exhaust valves were installed in each of a total of eight air supply and exhaust routes.

The rapid exhaust valve opens the path from upstream to downstream when the upstream pressure is higher than the downstream pressure, and opens the path from downstream to the exhaust path when the downstream pressure is higher than the upstream pressure. Generally, the exhaust path is opened to the atmosphere to speed up the exhaust operation of the pneumatic actuator. However, if the rapid exhaust valve is opened to the atmosphere in this device, the dropping motion cannot be stopped midway because of the two-step dropping presentation device. Therefore, an exhaust air control device was fabricated to control the exhaust of the rapid exhaust valve.

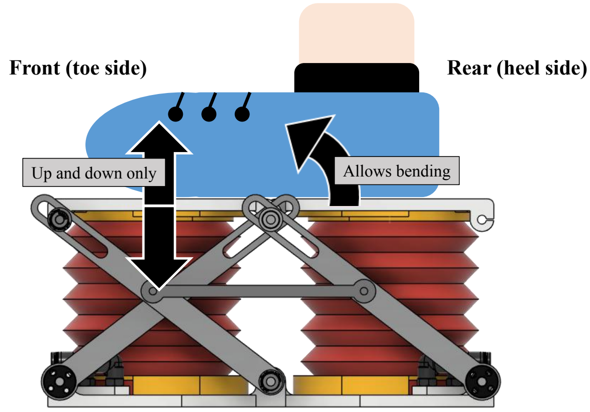

Figure 5. Image of device flexibility during walking

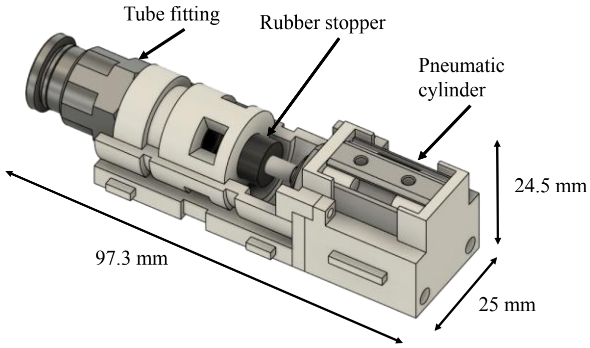

Figure 6. Overview of exhaust control device

Fig. 6 shows an overview of the exhaust air control device. The device consists of a structure made by a 3D printer, a tube fitting, a rubber plug, and a double-acting air cylinder (CJP2B10-5D, SMC). The exhaust path of the rapid exhaust valve is connected to the tube fitting, and the exhaust is controlled by a rubber plug attached to the air cylinder, which closes and opens the exhaust. This makes it possible to shut off the exhaust path of the device during the dropping motion and to stop the dropping motion in the middle of a drop. The operation realized by the device is the same as that of a standard direct-acting solenoid valve, but the orifice diameter is 6 mm, which is large for the size of the device, making it suitable for controlling large flow rates. On the other hand, the response is slower than that of solenoid valves due to the pneumatic differential, and this characteristic must be taken into consideration when precise control is required. In the case of this falling sensation presentation, precise control is not necessary, and the slow response can be adjusted by inputting the signal to the device earlier than the actual presentation timing.

This device is not directly attached to the bellows-type falling sensation presentation unit or to the user but is connected to the air tubing that leads to the device.

III. Two-Step Dropping Experiment

A two-step dropping motion experiment was conducted using the developed dropping motion presentation device. Experiments were conducted with weights placed on the device. Three types of weights (20 kg, 30 kg, and 40 kg) were used, and three experiments were conducted under each weight condition. Although the device is designed to be worn on both legs, the load was set to half of a person's body weight because the experiment was conducted on one leg.

A. Experimental environment of Two-step droppings

The pneumatic system connected to the dropping motion presentation device is shown in Fig. 7. Air from the compressor is sent to the dropping motion presentation device through a proportional control solenoid valve (ITV2050-213L5, SMC) and a rapid exhaust air control device (EQ02-C06P01C10, PISCO). During the dropping motion, the exhaust air is sent from the device to the exhaust air control device through rapid exhaust valves and is released to the atmosphere. The two-step dropping motion of the device is realized by the following procedure.

1. The device is kept elevated by an air pressure of 0.1 MPa.
2. The first step of the dropping process is initiated by decreasing the pressure command value of the proportional solenoid valve. At this time, the exhaust air control device is opened.
3. The exhaust air control device closes at the timing of the intermediate stop, which stops the dropping of the first step. At the start of the second-step dropping, the exhaust air control device is opened and the dropping motion starts again.

The two-step dropping motion was realized by the above method. The displacement of the dropping motion was measured using a laser displacement meter (HG1200, Panasonic). Experiments were conducted three times for each condition, and the average was calculated.

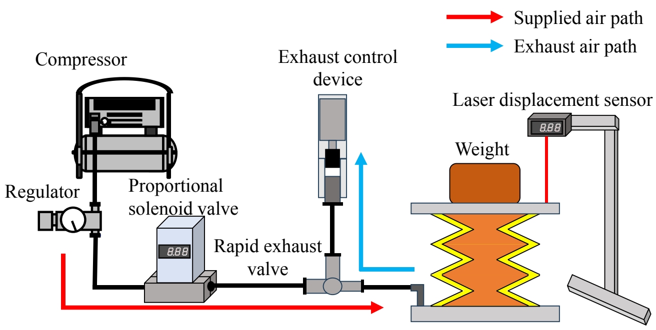

Figure 7. Pneumatic equipment for realization of two-step dropping motion

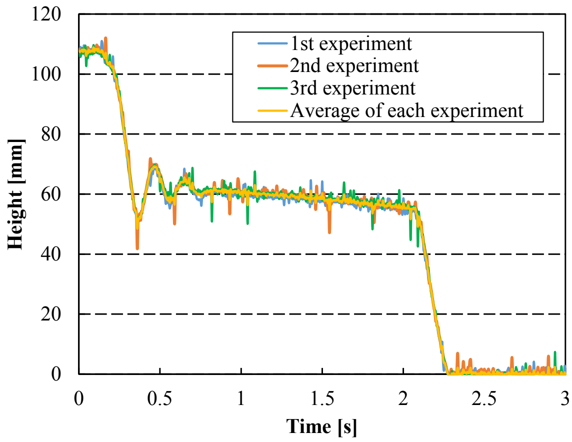

Figure 8. Graph of time variation of displacement during a two-step dropping experiment

B. Result of Two-step dropping experiment

Fig. 8 shows the time variation of displacement during a two-step dropping experiment with a 20 kg weight. In this experiment, the command to close the exhaust air control device was given 270 ms after the command to start the drop, in other words, the command for an intermediate stop was given. The graph shows that after the first-step dropping motion, the dropping motion was once suppressed at a height of approximately 60 mm, and then the second-step dropping motion was realized. The gradual drop continues even during the stop section, which is caused by a slight air leakage from the main body of the device. In the experiments using 30 kg and 40 kg weights, air leakage was so large when air pressure was applied that the device was feared to be damaged, so the experiments were suspended. However, we believe that the same operation can be achieved with larger weights by solving the problems of airtightness and durability. Therefore, based on the results of this experiment, we conclude that this device can be used as a falling sensation presentation device.

IV. WALKING FEELING EVALUATION EXPERIMENT

This chapter describes an experiment conducted to evaluate the comfort of walking while wearing the developed dropping motion presentation device. In the experiment, subjects walked naturally while wearing the dropping motion presentation device, and the comfort of walking and the feeling of fatigue were evaluated.

A. Experimental procedure

The experiment was conducted in the environment shown in Fig. 9. This experiment was conducted without VR headsets worn by the subjects. The experiment proceeded as follows.

1. At the beginning, subjects receive an explanation of the experiment.
2. Subjects practice walking while wearing the device.
3. The subject walks 3 m while wearing the device. The subject does not control walking posture, stride length, walking speed, etc., but walks naturally according to his/her condition.
4. Fill out a questionnaire about the sensation of walking.

Perform steps 2 through 4 above four times, once for each comparison condition.

As comparison conditions, an air cylinder type falling sensation presentation device (Cylinder type)[18] the device used in the previous study, an athletic shoe equipped a weight (Weighted shoes) equivalent to that of the bellows type falling sensation presentation device, and the subject's casual shoes (Casual shoes) were used, and each was tested under the same conditions.

The bellows-type falling motion presentation device developed in this study is improved in terms of weight and minimum height compared to the pneumatic cylinder-type device, which is a previous type, and therefore, each evaluation score is expected to exceed that of the pneumatic cylinder-type device. The weighted athletic shoe also has advantages compared to the bellows device, such as a lower minimum height and more flexibility, which can be used to compare the contribution of weight and other factors to the evaluation of each score. If there was no significant difference between the scores of the weighted athletic shoes and the bellows-type device, it means that the main factor affecting the score was weight. If this was not the case, it means that factors other than weight had a significant effect.

The record of ordinary shoes is for reference only and is not used for multiple comparisons. The bellows-type falling sensation device was placed over the subject's casual shoes. No air tubes were connected to either device during walking, and the air supply and exhaust ports were closed by inserting plugs so that they would not extend during walking. Also, the order in which each comparison condition was presented was randomly determined for each subject. Subjects in the experiment were 12 healthy adult males between the ages of 22 and 25 years old belonging to the same laboratory.

The following three questions were asked after the walk.
Q1. Was it comfortable to walk?
Q2. Did you feel at risk of falling when walking?
Q3. Did you feel the shoes were too heavy?

Responses to the questionnaire were completed on a 5-point Likert scale. Multiple comparisons were made using the Friedman test adjusted by the Bonferroni method. The subjects were also recorded walking from the side during the experiment, and the time taken to walk 3 m and the number of steps were measured from the recordings.

B. *Results of walking evaluation experiment*

Fig.10, Fig.11, and Fig.12 show the results of the questionnaire for the walking sensation evaluation experiment. The higher the score of each item, the better the sensation of walking. First of all, the evaluation of the normal shoes was significantly higher in each item, but since this is a reference record, we do not compare the results in this study. In the comparison of the three conditions excluding normal shoes, the bellows-type device scored the highest in all items. The results of the multiple comparison test show that the bellows-type device developed in this study scored higher than the air cylinder-type device used in the previous study in terms of the risk of falling and the sense of weight, which may indicate the design intention of reducing the height and weight of the device in the subjective evaluation by the subjects. In addition, there were no significant differences in the scores of ease of walking and risk of falling between the bellows-type device and weighted athletic shoes, which suggests that factors other than weight, such as shoe height and flexibility, have a small effect on these scores. However, as devices become lighter in the future, these factors may have a more significant impact on walkability.

Also, the time and number of steps required for a 3-meter walk shown in Fig. 13 and Fig. 14 indicate that the bellows-type device achieved better ease of walking than the cylinder-type device, with scores similar to those of weighted athletic shoes. The results of the multiple comparison test also showed a statistically significant difference between the scores of the bellows-type and cylinder-type devices. We think that this is a result of the improvements made to the device, such as the reduction of the device height and the improvement of stability through weight reduction, which are also reflected in the evaluation results.

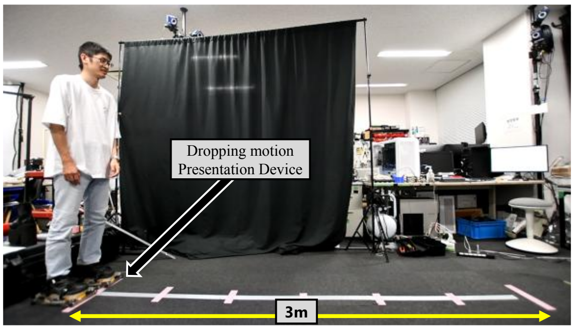

Figure 9. Environment of the walking sensation evaluation experiment

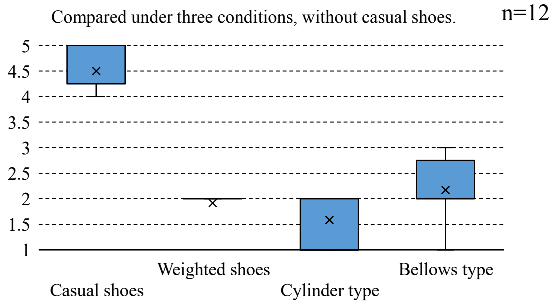

Figure 10. Results of a questionnaire about walkability

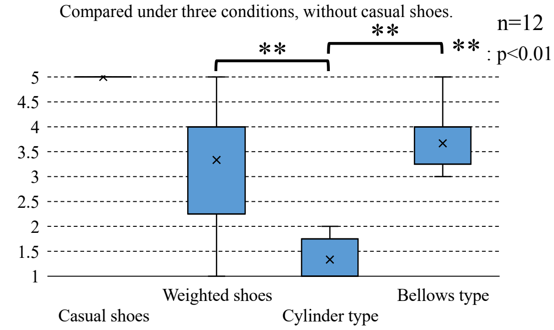

Figure 11. Results of a questionnaire about fall risk

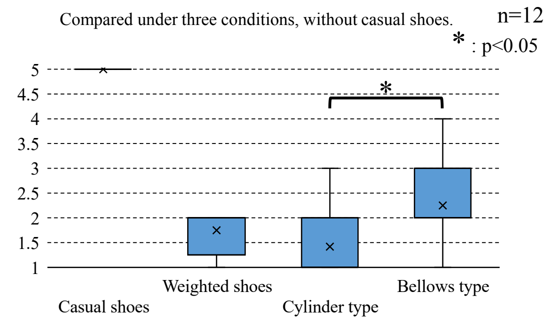

Figure 12. Results of questionnaire about heaviness

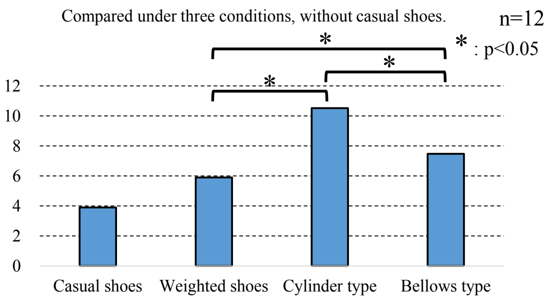

Figure 13. Average time taken by the subject to walk 3 meters

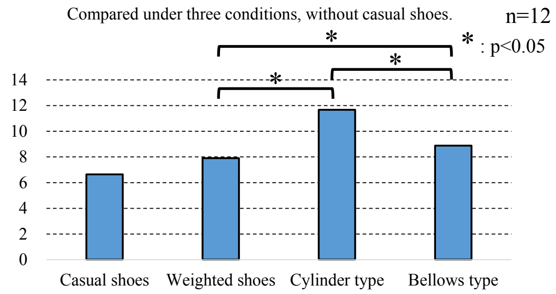

Figure 14. Average number of steps taken by the subject to walk 3 meters

On the other hand, when compared to the scores of casual shoes, which were obtained as reference, there is a significant difference among the other three conditions, including the developed device. This indicates that the developed device was very difficult to walk in compared to casual shoes. Therefore, the walkability of the developed device was not sufficient for absolute evaluation, and required further weight reduction, improved flexibility, and accurate fitting. However, it is difficult to improve the device to achieve ease of walking comparable to that of ordinary shoes. If the target is a general work safety shoe, it must be at least 1 kg lighter and more flexible, which is not easy to realize. Therefore, we think that this result indicates a certain limit to the concept of presenting an fall experience with a shoe-type device, in which the wearer may have to tolerate some discomfort in walking.

Finally, the evaluation environment for this experiment was simple compared to the expected environment in which the device would be used. The only movement performed in the experiment was a 3-meter move, and each trial was completed within 10 seconds in most cases. However, when the device is actually used as a wearable device, it is assumed that the user will experience a longer time while wearing the HMD, and that the wearer will not only move forward, but also turn around and move backward. These increase the wearer's instability, and we can expect that the evaluation of the risk of falling in these situations will have different evaluation values. However, in this experiment with only moving forward, there were clear differences in scores for the fall risk and objective evaluation items, and we believe that relative comparisons between the conditions were sufficiently made. Therefore, from the results of this experiment, it was concluded that the developed bellows-type device was more comfortable to walk on than the previous cylinder-type device.

V. Conclusion

This paper describes the development of a dropping motion presentation device to realize a method of reproducing a long-distance fall in a VR space by a short distance drop in a real space. The device was designed to be lightweight and bendable in order to make it comfortable to walk compared to previous devices. An exhaust air control device was also developed to control the large flow of exhaust air generated by the bellows actuator, and this device was used to realize a two-step dropping motion.

In the walking experiment, the developed device showed better scores than the previous device in both the subject's subjective sensation and objective evaluation items, indicating that the improvement of the device this time led to Enhanced walkability.

In the future, we will reevaluate after further improving the comfort of walking by adjusting each part of the device, and VR content that enables the wearer to experience falling, including walking motions, will be created to evaluate the effectiveness of this device in improving falling sensation.

Acknowledgment

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