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Grutio: System for Reproducing Swallowing Sensation Using Neck-Skin Movement

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ABSTRACT Many activities can be carried out in virtual reality environments, and at present, reproducing the activity of eating or drinking is one developing field. Virtual eating or drinking can be divided into two types: those with food in the mouth and those without placing food in the mouth. Many studies have focused on changing the taste, size, and texture of food when eating or drinking, but few studies have focused on recreating the sensation of eating or drinking without actually placing food in the mouth. One of the challenges in virtually reproducing eating or drinking without the use of food or drink is how the sensation of swallowing is recreated in the esophagus. Herein we show Grutio, a device for recreating the sensation of swallowing by causing skin deformations that are the same as those during actual swallowing. When participants were asked to compare the sensation of drinking water with the recreated sensation, 66% of the participants had a stable pattern of swallowing sensations over the three-day experiment. participants who did not have a stable pattern also felt swallowing at least three times, and all participants were able to feel swallowing. The hardness and viscosity of the virtual swallowed food could be changed by adjusting the rate of skin deformation. The system allowed most users to virtually feel the sensation of swallowing through calibration. Although there were individual differences, the results of this study suggest that applying skin deformations externally to the neck can reproduce swallowing sensations internally.

INDEX TERMS Haptic interfaces, virtual reality, augmented reality, swallowing, human food interaction.

I. INTRODUCTION

In this paper, we propose a method of reproducing the sensation of swallowing from skin deformation for virtual reality (VR) eating and drinking. Around the world, more and more experiences can be recreated in VR; for example, daily activities such as traveling, watching sports, and training can be experienced through various technologies in VR. The activities of eating or drinking are among the daily activities for which VR technologies are being developed. Human movement during eating and drinking has been well studied, and five stages represent the physiological model of swallowing: cognition, movement, mastication, swallowing (pharynx), and esophageal passage [1], [2]. All five senses are generally used in eating and drinking, such as sight and smell in the cognitive phase, touch in the movement phase, taste, smell, and hearing in the mastication phase. This is one reason why the activity of eating or drinking is more complex to reproduce than that in other experiences.

Eating and drinking using virtual reality technology can be categorized into two main types: one is Virtual-eating, which reproduces the sensation of eating and drinking without using actual food and drink. The other is Augmented-eating, which changes or extends the sensation of actually eating and drinking. Virtual-Eating is an important technology to increase QoL for those who cannot eat and drink due to illness or diet. In current research on Virtual-Eating, Hashimoto *et al.*'s straw-like user interface to make users feel as if they are drinking something by simulating vibrations and pressure instead of drinking it Sasakawa *et al.* [3] and Niijima *et al.*'s proposal of food texture by electric muscle stimulation [4]. In Augmented-Eating, studies such as MetaCookie [5] and Voctail [6] have been conducted to change the amount and taste of something eaten by changing its appearance when

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eating it. The illusion of quantity and taste has been used to create health-related effects such as satiety with small amounts of food and low salt content and create new textures. These studies aimed to alter the taste, texture, or amount of something in the mouth, and most only focused on the cognition to the mastication phases of the physiological swallowing model. However, when considering virtual eating or drinking without placing anything in the mouth, it is a challenge to create the sensory perception of the esophageal phase of swallowing. When food or drink is ingested, the food or drink passing through the esophagus will give the sensation of swallowing, but when nothing is ingested, it is necessary to find a method of reproducing this sensation. In Japanese, the word ''nodogoshi'' refers to the sensation of going down the throat of food and drink, and the sensation of going down the throat of some foods such as beer and noodles is often enjoyed. This suggests that the sense of swallowing is an important factor in eating and drinking, as well as taste and oral sensations. The feeling of swallowing is an essential element in the experience of eating and drinking and is an essential element in virtual eating and drinking that does not use food or drink.

In this study, we focused on the sensation of swallowing to realize virtual eating and drinking. In addition to fulfilling nutritional requirements, diet is an essential factor for maintaining the quality of life through the pleasurable experience of taste and communication with others. By making it possible to experience eating and drinking without actually eating ingesting anything, more people with dysphagia and others who have difficulty in swallowing or eating will be able to enjoy eating and drinking again, even though the number of people with dysphagia and other disorders is increasing worldwide. In this study, we proposed a method to produce the sensation of swallowing by causing skin movements similar to peristalsis, i.e., making the skin around the throat move in the same way as it would during swallowing. During regular swallowing movements, the skin around the throat moves as a result of the movement of the underlying bones and muscles—a subordinate action occurs along with the conscious action, and the sensation is obtained. Such a model of command-movement-sensation takes place in many everyday actions. We hypothesized that it might be possible to cause the perception of the conscious action by reproducing a subordinate action. We developed a prototype device called Grutio that was designed to reproduce the sensation of swallowing for the user by moving the skin around the throat. This paper describes related research in Section II, the device and system configuration in Section III, the evaluation method and experimental results of the device and system in Section IV, and the results are summarized and discussed in Section V.

II. RELATED WORKS

When we consider virtual eating and drinking, it is important to imitate the physiological eating and drinking movements. There are separate physiological models for liquids and for solids. For swallowing liquids, 4- or 5-stage models exist [1], [2]. The 4-stage model is categorized into oral preparatory, oral transit, pharyngeal, and esophageal phases, whereas in the 5-stage model, the oral cavity is considered independent of the pharynx, and the pharyngeal phase is subdivided accordingly. For swallowing solids, the process model is classified into four stages: stage 1 transport, stage 2 processing, stage 3 transport, and stage 4 swallowing [7], [8]. In the oral preparatory phase, the senses of sight, smell, and touch are used for seeing the food or drink, smelling the food or drink, and moving food to the mouth. Previous studies on affecting the sense of touch have included gravitaminic acid [9], which mimics a seasoning that changes weight. Another example was MetaCookie+ [5] that aimed to influence taste by changing visual and olfactory sensations; the appearance of cookies was changed by HMD, and the taste of cookies was changed using different aromas. In the oral transit phase and the pharyngeal phase, the senses of hearing, taste, smell, and touch are used. Several methods to change food texture during mastication have been developed, such as presenting chewing sounds via the temporomandibular (TMJ) using bone conduction [10] and creating a virtual texture with electromyostimulation (EMS) around the TMJ [4]. The esophageal phase is thought to mainly be related to the sense of touch, but most research until now has mainly been concerned with changing the taste and texture of food or drink by presenting sensory information during actual eating and drinking processes.

In this study, we focused on the sensation (sense of touch) after the third phase (pharyngeal). In medicine and rehabilitation, larynx elevation support using electrical stimulation has been proposed. Percutaneous and epidermal electrical stimulation of the hypoglossal muscles, which are related to swallowing, assist in lifting the larynx [11], [12]. However, stimuli that cause subluxation of the hyoid bone have been noted to have the potential to cause aspiration [13]. Currently, safety guidelines for the use of electrical stimulation are being studied [14]. Aspiration, including aspiration pneumonia, is a serious or life-threatening risk. Older adults are at even greater risk because they have particularly weak swallowing-related muscles. Also, it is generally accepted that the results of EMS vary widely among individuals. Although it is possible to stimulate the muscles directly, there are individual differences in methods of stimulation, and it is difficult to make EMS work effectively. At the same time, effective use of these systems often requires specialized knowledge. It is necessary to know the location of nerves and muscles and to apply the current to the appropriate location. Although the risks associated with EMS can certainly be reduced by optimal manipulation, from an ease-of-use perspective, a less invasive and less risky method uses skin stimulation. The SUI [15] is an example of an attempt to reproduce the sensation of drinking. A device that simulates the sound, vibration and pressure change of drinking through a straw was developed to simulate the sensation of drinking without ingestion though it cannot be said that these devices reproduce meals, since they are mainly addressing

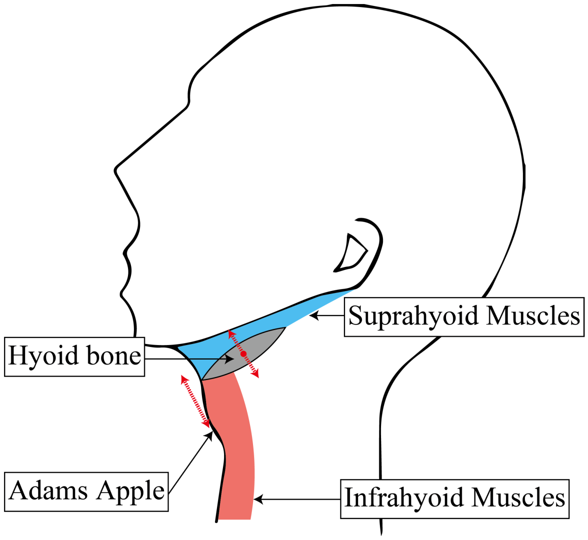

FIGURE 1. Swallowing device mechanisms of action.

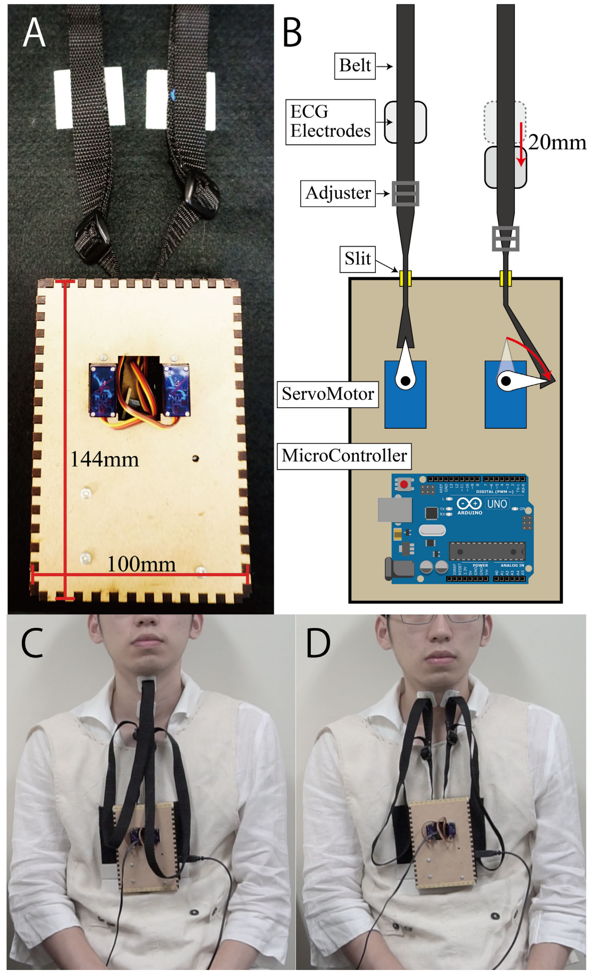

FIGURE 2. (A) A photograph, (B)Diagram of Grutio components(left belt figure shows the initial position and right belt figure shows when it moves), (C)Device installation example: vertical pattern, and (D)Device installation example: horizontal pattern.

the first and second phase. In this study, the skin action during swallowing was replicated through adhesive traction attached to the throat near swallowing-related muscles to generate the feeling of swallowing. By generating the sensation of swallowing, it is possible to mimic the postpharyngeal phase of the swallowing model. The only adhesive is applied, which is less invasive than electrical stimulation, and the risk of aspiration is reduced because the patient does not experience an actual swallowing reflex.

III. GRUTIO: SWALLOWING SENSE PRESENTING DEVICE

A. SWALLOWING SENSATION

Briefly, the anatomy and physiology of swallowing are described. Food and drink are first chewed in the mouth to form a food mass. The reflexive movement of the tongue and jaw is used to swallow. During swallowing, supraglottic and subglottic muscles move the hyoid bone forward and upward, and at the same time, the larynx is raised (Fig. 1). This suggests that the sensation of swallowing is caused by the action of swallowing-related muscles(Suprahyoid muscles, Infrahyoid muscles) and the sensation of a food mass passing through the pharynx; however, the pharynx is located in the innermost part of the mouth, making it difficult to apply any sensation directly. In this study, we used a method that moves the hyoid and larynx upward to simulate swallowing with resulting skin deformations. It is thought that it is by regularly feeling the movement of the skin of the throat area, that the sensation in the throat associated with swallowing is actually learned; therefore, we wondered if it would be possible to create the illusion of swallowing by mimicking this movement using external skin stimuli.

B. GRUTIO COMPONENTS

Fig. 2 shows the appearance and configuration of the device developed in this study. The system consists of a servo motor (SG90), belt with adjuster, adhesive electrodes (3M monitoring electrode 2228), and microcontroller (Arduino Uno). New adhesive electrodes are used for each user to maintain hygiene. The device uses a servo motor inside the case to pull the belt that is attached to the skin at the position where the electrocardiogram electrodes are attached (Fig. 2). The device operates by commands from the connected laptop and performs preprogrammed actions. The traction speed by the servo motor can be set to any speed between 1 cm/s and 16 cm/s and the stroke length is 20 mm The device weighs approximately 210 g and is 144 mm × 100 mm × 40 mm. The length of the traction of 20 mm was determined based on the average of the results of the investigation of the amount of hyoid bone movement in previous studies. [16]

C. MOVEMENT PATTERN

Experiments were conducted using two attachment patterns, which are shown in Fig. 3 and Fig. 4

For the vertical pattern, adhesive electrodes were attached to the upper and lower portions of the front central larynx.

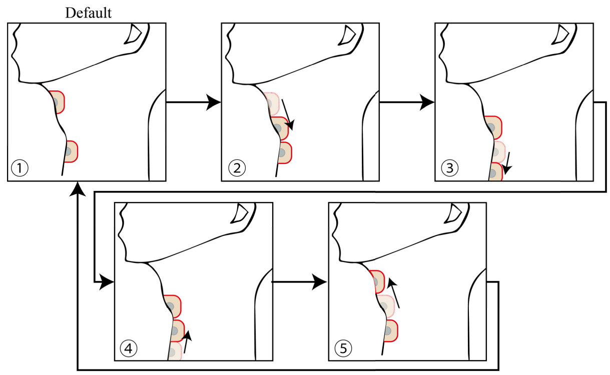

FIGURE 3. Vertical movement pattern.

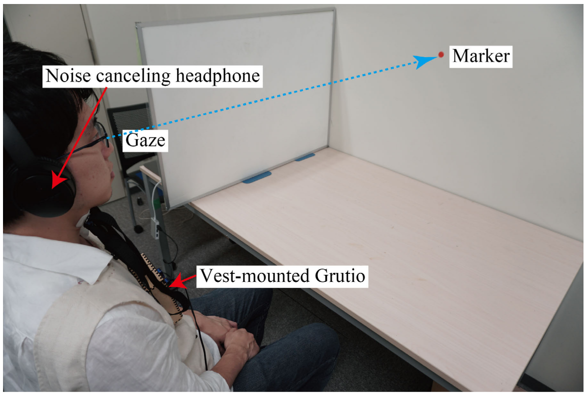

FIGURE 5. Experimental environment.

As shown in Fig. 3, the adhesive electrode is moved up and down with a difference of about 100 ms. By moving the skin of the user's throat in this way, hyoid bone and muscle movements from peristalsis during swallowing in the esophageal phase are reproduced. Also, because the attachment position is above and below the larynx, it is possible to present stimuli to both supraglottic and subglottic muscle groups.

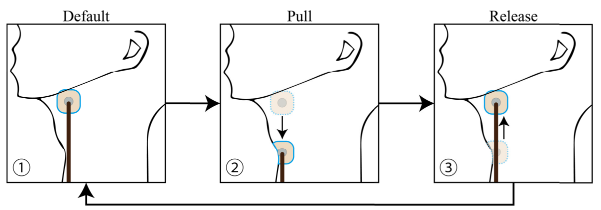

FIGURE 4. Horizontal movement pattern.

For the horizontal pattern, the adhesive electrodes attached to both upper sides are moved at the same time (Fig. 4). To reproduce the movement of the hyoid and larynx during swallowing, the skin on the throat was made to move from the traction state to the normal state (the traction state is released first), and then the sensation of the skin moving upward was presented. After that, there was immediate traction for the esophageal phase of the food lump, with the presentation of a sensation of moving downward to return to the normal state.

IV. EVALUATION

A. EXPERIMENT

We conducted an evaluation experiment to confirm whether the proposed method and the device we created could present the feeling of swallowing. This research is intended to be eventually used in immersive environments such as VR. However, in an immersive environment, visual and force factors are increased, and it is not suitable to evaluate the swallowing sensation given to the subject by the device compared to an experiment with the only sensation. Therefore, in this experiment, we will conduct the experiment in real space and passively receive sensations. The participants were students in our university who had no swallowing difficulties and no abnormalities in the cervical skin, 8 males and 1 females. Their age ranged from 21 to 24 ($M = 22.2$, $SD = 0.92$). All participants were recruited from the members of our university mailing list. All participants participated in the experiment without compensation. All of them had a technical background in computer science or engineering.

The experimental procedure was as follows:

1) The participant sat in the chair as shown in Fig. 5.
2) The participant faced forward with a marker in the center of their field of view.
3) The experimental device was worn attached to a vest.
4) Adhesive electrodes were attached to the throat (according to the experimental pattern)
5) Repeated swallowing stimuli were presented three times.
6) The participant drank (ingested) water.
7) The participant completed a questionnaire comparing the feeling of drinking water with the stimuli presented by the device.
8) The speed and pattern of the movements were changed (repeated step 5-7 three times each).

The above procedure was used for one day, and all participants participated in three experiments with at least one day in between. Each day's experiment took approximately one hour to complete. By repeating the experiment on completely different days, we can expect to confirm whether or not there is a change in the pattern of susceptibility to swallowing sensation within the participants.

The conditions were the same for both posture identity and environmental and system operating noise experiments. We used a chair fixed to the floor, and markers were placed on the wall for the participant to fix their gaze while maintaining the same postural position during the experiments. Also, participants wore noise-canceling headphones that played white noise at a sufficient volume to suppress environmental and motion sounds. This experiment was performed with the approval of the University of Electro-Communications Ethics Review Committee (No.19021).

FIGURE 6. The posture of the participant while wearing the experimental apparatus.

1) QUESTIONAIRE

The questionnaire contained the following three questions and a place for free-text comments.

Q1 Did you feel that you swallowed something?
Q2 Did you feel similar to the feeling of drinking water?
Q3 Did you feel close to the movement of your throat when you swallowed something?

These questions were answered using a 6-point Likert scale, with 1 being negative (low) and 6 being positive (high). The six-point Likert scale is an irregular method; however, a median point indicating "neither" makes it difficult to evaluate indistinct sensations such as the swallowing sensation in this case. The free-text description comment was optional.

2) EVALUATION PATTERN

For vertical movements, we used five patterns: 1 cm/s, 3 cm/s, 5 cm/s,7 cm/s, and a combination of randomly set speeds. For horizontal movements, the same speeds were used, and pharyngeal and esophageal transit times when actually drinking water were used as references [7]. The real pattern was designed to operate with an upward-opening time of approximately 0.2 seconds and a downward pulling time of 0.8 seconds. The random pattern was generated in advance, and the same pattern was used in all three experiments. The order of presentation was determined at random, presented to all participants in the same order, and the questionnaire was completed at the end.

TABLE 1. The descriptive statistics value (median, mean, and standard deviation) of the questionnaire.

		Vertical Pattern			Horizontal Pattern		
Question	Speed	Avg.	Median	SD	Avg.	Median	SD
Q1	1cm/s	2.573	3	1.051	2.646	3	1.217
	3cm/s	2.963	3	1.071	2.854	3	1.101
	5cm/s	2.939	3	1.124	2.902	3	0.999
	7cm/s	3	3	1.065	2.927	3	0.961
	Random	2.531	2	1.101	1.716	2	0.789
	Representation	N/A	N/A	N/A	3.037	3	1.082
Q2	1cm/s	2.085	2	0.976	2.293	2	1.073
	3cm/s	2.549	2	1.019	2.549	2.5	1.123
	5cm/s	2.543	2	1.049	2.415	2	0.963
	7cm/s	2.573	2	1.055	2.463	2	1.086
	Random	2.148	2	1.198	1.358	1	0.759
	Representation	N/A	N/A	N/A	2.556	2	1.018
Q3	1cm/s	2.341	2	0.973	2.317	2	1.176
	3cm/s	2.78	3	0.875	2.671	3	1.018
	5cm/s	2.878	3	1.008	2.683	2.5	0.932
	7cm/s	3.037	3	1.171	2.756	2	1.071
	Random	2.407	2	1.255	1.358	1	0.725
	Representation	N/A	N/A	N/A	2.815	3	0.957

V. RESULT AND DISCUSSION

The descriptive statistics value (median, mean, and standard deviation) of the questionnaire results for all the patterns obtained are shown in Table 1. These three questions in this questionnaire are based on a 6-point Likert scale. Therefore, all the data are treated as an ordinal scale. As a result, there was no pattern with a typical value exceeding 3.5, which is the central value, and we could not find any effective pattern that applies to many users. However, when we turned our attention to individual users, we found that each user had an effective, though not general, pattern. Most users could feel the swallowing sensation and had a stable effective pattern throughout the three days of the experiment.

First, to test for normality, a Shapiro-Wilk test was performed for each speed of the two pasting patterns. As a result, normality was rejected for all patterns ($p<0.05$). Based on the above, we treat all the data obtained in this study as non-parametric data. Next, to test if there is a difference in the results of each question between the two pasting patterns, we performed the Friedman test, a non-parametric test that tests the difference in means. However, among the speed patterns, the pattern reproduced in the parallel configuration is not present in the perpendicular configuration, so it has been removed from the test. The basic statistics of the results of the Friedman test, the p-value and the effect size w for each question are shown in Table 2. The results of the Friedman test suggested that only the similarity of the throat movements in Q3 differed according to the pattern of tape application. The p-value for Q1 and Q2 was >0.05, rejecting the hypothesis of a difference in the means. The effect size w was also sufficiently large to be reliable. This suggests that there is no difference in the overall mean scores for the questions related to swallowing sensation. However, the p-value < 0.05 for Q3 supports the hypothesis that there is a difference in the means. The effect size is 1, which is a very large score, and the results are sufficiently reliable. As shown in Table 1, the vertical pattern outperformed the horizontal pattern in all five velocity and random patterns. This means that overall, the Vertical pattern is better at reproducing the throat movements during swallowing.

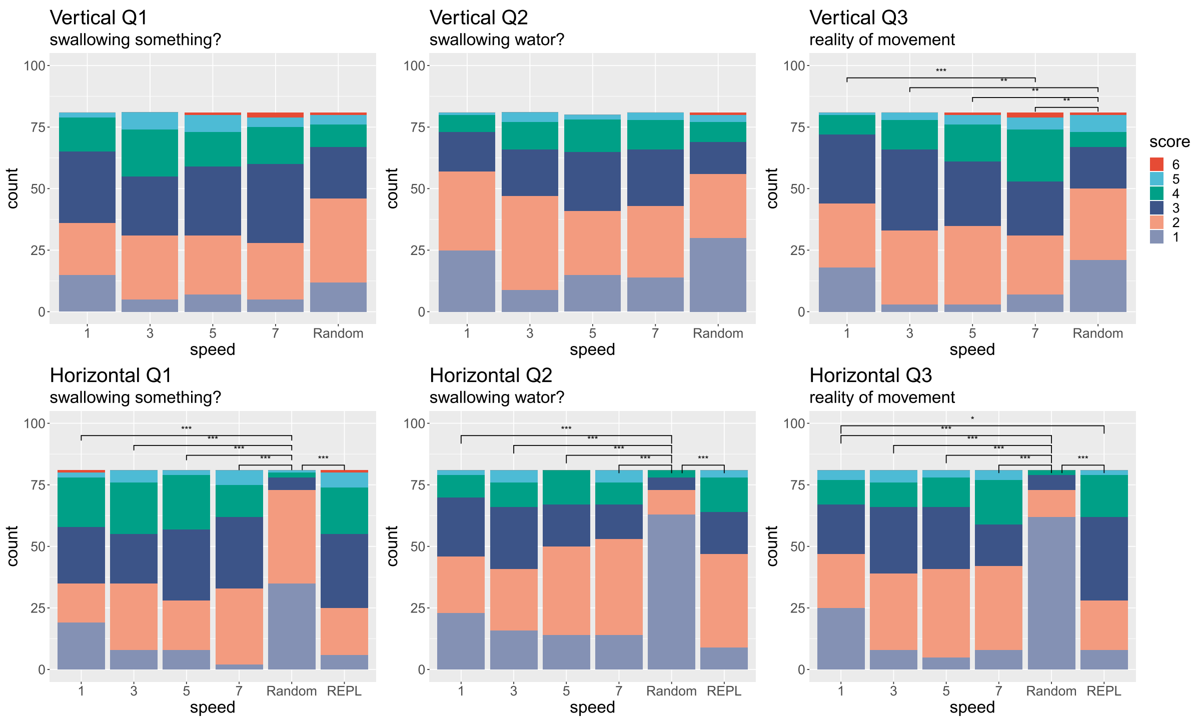

FIGURE 7. **Results of multiple comparisons by Wilcoxon's rank sum test for each question.**

TABLE 2. **Result of Friedman's test.**

Question	p-value	w:effsize
Feeling of having drunk water or not	0.18	0.36
Feeling of having drunk something or not	0.317	0.2
Similar to move of throat when drinking water	0.0253	1

Next, to test whether there was a difference in the results of each question depending on the speed of presentation within each pasting pattern, we conducted a multiple comparison test using Wilcoxon's rank-sum test. The Holm method was used to correct for the multiple comparisons. The results are shown in the following Fig.7 and Table 3. In Q1 and Q2, there was no difference between the speed patterns in terms of swallowing sensation for the vertical placement pattern. However, there was a difference in the approximation of the movements in Q3. There is a significant difference at p<.01 between the 1cm/s and Random patterns, which have relatively low mean values, and the 7cm/s pattern, which has the highest score. The next highest score, 5cm/s, also shows a significant trend at p<.1. These results show the relatively high speed of more than 5cm/s pattern is effective for enhancing the reality of swallowing motion in a vertical pattern. On the other hand, extremely slow speeds(1cm/s) and random patterns with modulation of speed were not effective in creating a sense of motion reality. In the horizontal pattern, there is a strong significant difference of p<.01 in all questions between the random pattern and all other patterns. In this study, the random pattern in the horizontal placement pattern was independent of the left and right movement, and the two parallel tapes operated at completely different speeds and timings. Therefore, it is thought that the actual swallowing sensation was different. In other patterns, the left and right tapes moved up and down simultaneously with at least the same speed, suggesting that when the tapes are placed in parallel, the reality and swallowing sensation can be enhanced by moving multiple tapes simultaneously and at the same speed.

In this experiment, we collected data for a total of three days to see the differences between individuals and the changes on different days. Average of the differences are 3.31 days and SD = 1.71 days. The following Tables 4 and 5 list the median values for three days each subject and the standard errors calculated from the daily means for each subject. The questionnaire was administered using a 6-point Likert scale, with scores varying in increments of 1. Therefore, if the standard error does not exceed 0.5, which can be regarded as a change of more than 1 by rounding up, it can be regarded as a sufficiently stable presentation of the sensation.

As a result, six of the nine participants were able to feel a stable swallowing sensation at least one of the combinations of patterns and speeds. The remaining three participants also felt the swallowing sensation at least a few times, and none of them could feel it at all, although the typical value was less than 3.5 and the error was large and unstable. In the vertical pattern, participants D, J, and K felt that they had swallowed something, and participants H and I felt that they had swallowed water. In the horizontal pattern,

TABLE 3. Result of multiple comparison test using Wilcoxon's rank-sum test for each speed for each pasting pattern.

(a) Horizontal Pattern Q1 (*:p<.1, **:p<.05, ***:p<.01)

Speed\Speed	1cm/s	3cm/s	5cm/s	7cm/s	Random
3cm/s	1	N/A	N/A	N/A	N/A
5cm/s	1	1	N/A	N/A	N/A
7cm/s	1	1	1	N/A	N/A
Random	***	***	***	***	N/A
Representation	0.81	1	1	1	***

(b) Vertical Pattern Q1 (*:p<.1, **:p<.05, ***:p<.01)

Speed\Speed	1cm/s	3cm/s	5cm/s	7cm/s
3cm/s	0.83	N/A	N/A	N/A
5cm/s	1	1	N/A	N/A
7cm/s	1	1	1	N/A
Random	1	0.12	0.51	0.51

(c) Horizontal Pattern Q2 (*:p<.1, **:p<.05, ***:p<.01)

Speed\Speed	1cm/s	3cm/s	5cm/s	7cm/s	Random
3cm/s	1	N/A	N/A	N/A	N/A
5cm/s	1	1	N/A	N/A	N/A
7cm/s	1	1	1	N/A	N/A
Random	***	***	***	***	N/A
Representation	1	1	1	1	***

(d) Vertical Pattern Q2 (*:p<.1, **:p<.05, ***:p<.01)

Speed\Speed	1cm/s	3cm/s	5cm/s	7cm/s
3cm/s	0.66	N/A	N/A	N/A
5cm/s	0.94	1	N/A	N/A
7cm/s	0.66	1	1	N/A
Random	1	0.31	0.66	0.41

(e) Horizontal Pattern Q3 (*:p<.1, **:p<.05, ***:p<.01)

Speed\Speed	1cm/s	3cm/s	5cm/s	7cm/s	Random
3cm/s	0.675	N/A	N/A	N/A	N/A
5cm/s	0.566	1	N/A	N/A	N/A
7cm/s	0.445	1	1	N/A	N/A
Random	***	***	***	***	N/A
Representation	**	1	1	1	***

(f) Vertical Pattern Q3 (*:p<.1, **:p<.05, ***:p<.01)

Speed\Speed	1cm/s	3cm/s	5cm/s	7cm/s
3cm/s	0.116	N/A	N/A	N/A
5cm/s	0.116	1	N/A	N/A
7cm/s	**	1	1	N/A
Random	1	**	**	***

TABLE 4. Median and standard error by speed for each subject in vertical pattern.

	Subject	A		C		D		E		F		H		I		J		K	
	Speed	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE
Q1	1cm/s	2	0.272	3	0.471	4	0.157	3	0.272	3	0.272	3	0.471	3	0.629	2	0.314	3	0.816
	3cm/s	2	0.314	2	0.314	4	0.272	3	0.272	3	0.416	2	1.247	3	0.567	3	0.471	4	0.685
	5cm/s	2	0.314	3	0.272	3	0.236	3	0.749	3	0.416	2	0.471	3	0.544	5	0.314	4	0.157
	7cm/s	2	0.720	3	0.685	3	0.416	3	0.416	2	0.314	2	0.416	3	0.314	5	0.629	4	0.471
	Random	2	0.416	2	0.272	2	0.314	2	0.471	3	0.314	2	0.416	2	0.685	4	0.685	2	0.567
Q2	1cm/s	2	0.272	2	0.567	2	0.157	2	0.720	2	0.685	3	0.416	2	0.272	1	0.314	2	0.544
	3cm/s	2	0.471	2	0.272	2	0.272	3	0.314	3	0.272	4	1.030	3	0.157	1	0.416	3	0.567
	5cm/s	2	0.272	2	0.567	2	0.079	3	0.685	2	0.272	3	0.416	4	0.416	2	0.157	3	0.272
	7cm/s	2	0.831	3	0.471	1	0.567	2	0.000	2	0.416	2	0.544	4	1.133	2	0.416	3	0.685
	Random	3	0.416	1	0.416	1	0.157	2	0.629	2	0.629	3	1.100	1	0.875	1	0.416	2	0.314
Q3	1cm/s	2	0.157	2	0.416	3	0.272	3	0.314	2	0.720	3	0.157	3	0.567	2	0.567	2	0.544
	3cm/s	2	0.314	2	0.157	3	0.157	3	0.157	2	0.314	3	0.875	3	0.471	3	0.157	3	0.720
	5cm/s	2	0.157	3	0.272	2	0.157	3	0.749	2	0.157	3	0.629	3	0.314	4	0.567	3	0.272
	7cm/s	2	0.471	4	0.567	2	0.567	3	0.816	2	0.000	3	0.416	3	0.314	5	0.416	4	0.471
	Random	3	0.416	1	0.416	2	0.000	2	0.272	2	0.956	3	0.314	2	0.685	2	1.771	2	0.272

TABLE 5. Median and standard error by speed for each subject in horizontal pattern.

	Subject	A		C		D		E		F		H		I		J		K	
	Speed	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE	Med	SE
Q1	1cm/s	1	0.272	3	0.416	4	0.157	4	0.416	3	0.157	3	0.471	3	0.272	1	0.567	3	0.471
	3cm/s	2	0.272	2	0.157	4	0.416	3	0.416	3	0.416	3	0.831	3	0.157	4	0.567	4	0.629
	5cm/s	1	0.685	3	0.720	3	0.471	3	0.157	2	0.567	3	0.567	3	0.567	4	0.416	4	0.416
	7cm/s	2	0.314	3	0.272	3	0.157	3	0.272	2	0.000	2	0.544	3	0.157	4	0.000	3	0.272
	Random	1	0.157	1	0.157	2	0.157	2	0.157	2	0.157	2	0.157	1	0.157	1	0.471	2	0.000
	REPR	2	0.314	2	0.272	3	0.314	3	0.416	3	0.272	3	0.831	3	0.272	5	0.685	4	0.157
Q2	1cm/s	1	0.416	2	0.567	3	0.544	4	0.272	3	0.416	3	0.314	3	0.416	1	0.157	2	0.567
	3cm/s	2	0.157	2	0.314	3	0.544	4	0.831	2	0.314	3	0.416	3	0.157	1	0.416	3	0.416
	5cm/s	2	0.685	2	0.272	2	0.272	3	0.314	2	0.567	3	0.416	4	0.471	2	0.272	3	0.314
	7cm/s	3	0.272	2	0.272	2	0.157	2	0.416	2	0.567	2	0.720	4	0.157	2	0.272	2	0.157
	Random	1	0.157	1	0.000	1	0.000	1	0.272	1	0.314	3	0.000	1	0.272	1	0.000	1	0.000
	REPR	2	0.544	2	0.157	2	0.157	2	0.943	2	0.629	2	0.720	4	0.544	3	0.471	4	0.157
Q3	1cm/s	1	0.567	1	0.157	3	0.416	3	0.471	2	0.272	3	0.272	3	0.272	1	0.272	3	0.314
	3cm/s	2	0.314	2	0.000	3	0.272	4	0.786	2	0.000	3	0.416	3	0.157	3	0.567	3	0.471
	5cm/s	2	0.544	2	0.272	3	0.000	3	0.629	2	0.000	3	0.471	3	0.567	3	0.720	3	0.471
	7cm/s	4	0.416	2	0.471	3	0.416	2	0.314	2	0.314	2	0.567	3	0.314	4	0.157	2	0.314
	Random	1	0.157	1	0.000	1	0.157	1	0.272	1	0.157	3	0.157	1	0.157	1	0.000	1	0.000
	REPR	3	0.875	2	0.157	3	0.000	3	0.471	2	0.157	3	0.567	3	0.272	4	0.831	4	0.157

participants D, E, J, and K felt that they had swallowed something, and participants E, I, and K felt that they had swallowed water. The results show that each subject was able to feel swallowing sensation in different patterns. For example, in Q1, subject D felt the sensation of swallowing something at a speed of 1,3 cm/s, while subject J felt the

TABLE 6. All responses of the negative representative value participants in Q1.

Subject	Speed	Day1			Day2			Day3		
A	1cm/s	2	2	2	2	3	2	1	2	2
	3cm/s	2	2	2	3	2	1	2	1	1
	5cm/s	3	1	2	3	2	1	2	1	1
	7cm/s	3	2	4	3	1	1	2	1	1
	Rand	1	4	4	2	2	3	2	2	2
C	1cm/s	4	1	4	3	1	2	3	3	3
	3cm/s	3	2	4	2	3	2	2	2	3
	5cm/s	4	3	2	3	2	3	2	2	3
	7cm/s	3	3	2	1	3	2	3	4	4
	Rand	4	1	2	1	2	2	2	2	2
F	1cm/s	3	4	3	3	2	3	2	2	5
	3cm/s	4	3	3	5	4	3	4	2	3
	5cm/s	2	2	4	4	4	3	3	2	4
	7cm/s	2	2	2	3	3	2	3	2	3
	Rand	3	3	3	3	2	2	3	4	2

sensation at a random pattern of 5,7 cm/s, and subject K felt the sensation at a speed of 3,5,7 cm/s. There was a large difference between the individual participants. In the question about the sensation of swallowing water in Q2, it can be seen that there are individual differences, such as subject H is more likely to feel it at 3 cm/s and subject I at 5,7 cm/s. Of the subject-speed combinations with median values greater than 3 in the result, only one subject, Subject H, had an unstable value with a standard error greater than 0.5. Except for Subject H, the participants who were able to feel the swallowing sensation had a very stable combination pattern of feeling the swallowing sensation with a standard error of less than 0.5. This suggests that it is possible to present a more stable swallowing sensation by calibrating the parameters specific to each subject.

In addition, the following Table 6 shows all the responses to Q1 from participants who cannot felt swallowing sensation with a median of less than 3 across the three days. These members experienced swallowing sensations at least three times, although the pattern varied from day to day. In other words, all the participants could feel a swallowing sensation with the proposed device Grutio in this experiment.

TABLE 7. Correlation coefficients and significant differences among Q1, Q2, and Q3(*:p<.01,**:p<.05).**

	Q1-Q2		Q1-Q3		Q2-Q3	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
1cm/s	0.745***	0.567***	0.758***	0.721***	0.808***	0.540***
3cm/s	0.635***	0.516***	0.788***	0.605***	0.688***	0.501***
5cm/s	0.578***	0.446***	0.677***	0.669***	0.673***	0.539***
7cm/s	0.278**	0.505***	0.659***	0.731***	0.540***	0.645***
RAND	0.517***	0.543***	0.624***	0.667***	0.805***	0.745***
REPL	0.554***		0.777***		0.617***	

Table 7 shows the results of pairwise correlations and their significant differences for each question in Q1-Q3. Each number indicates the correlation coefficient, * indicates that the result is significant, *** indicates p<.01, ** indicates p<.05. Since this questionnaire is an ordinal scale, the Spearman method was used to calculate and test the correlation. The results showed that the correlation was strongly significant at p<.05 for speed 7cm/s and p<.01 for the other speeds in the horizontal pattern of Q1-Q2. The correlation coefficients were 0.5 or higher for Q1-Q2 except for 7cm/s of the horizontal pattern and 5cm/s of the vertical pattern. The correlation coefficients were 0.7 or higher for nine combinations, indicating a strong positive correlation for most patterns. The positive correlation between Q1 and Q2 and Q3 suggests that the more similar the presented movements are to those during swallowing, the more realistic the presentation of swallowing sensations becomes. There is also a positive correlation between Q1 -Q2, but most of them have a correlation coefficient of about 0.5, except for 1,3 cm/s in the horizontal pattern, and the correlation is not as strong as Q1-Q3 and Q2-Q3. As can be seen from the individual results mentioned above, the pattern of getting the sensation of drinking water and the pattern of getting the sensation of swallowing something is not necessarily the same for some participants. This suggests that it may be necessary to change the speed and presentation pattern for the sensation of drinking water and the sensation of swallowing something other than water. Comparing the vertical patterns Q1-Q3 and Q2-Q3, the correlation tends to be stronger in the case of Q2, except for the random pattern. In the vertical pattern, the approximation of the action may be directly related to the sensation of drinking water. A possible reason for this is that some people drink water in a pouring motion, which requires less throat movement than solid food. The design of the vertical pattern mimics the peristaltic motion during swallowing and does not replicate the motion of the hyoid bone as well as the horizontal pattern. Therefore, the vertical pattern is close to the sensation of food and drink passing by, which may have resulted in this result.

In this experiment, we set up a column for free comments in the questionnaire for each pattern. As a result, we received 124 comments from 5 of the 9 participants. We received 124 comments from 5 of the 9 participants, 36 of which were about what kind of food/drinks they felt swallowing. The free-text comments suggest that different patterns and speeds of presentation may result in different images of the nature of the swallowed food. The results are summarized in the following Tables 8 and 9.

In the horizontal pattern, subject E commented that at 3, 5, and 7 cm/s, and subject G, K commented that at 7 cm/s it felt like swallowing solid food. Also, participants E at 1, 3, and 5 cm/s and participants I at 5 cm/s commented that it felt like a viscous liquid. In the case of Subject E, the slower the speed, the greater the viscosity or volume of the liquid. (runny liquid → thick ramen noodles soup, corn potage → sorbet-like, gulping lots of water) For solid foods, 3,5 cm/s was commented for big meat and steak, 7 cm for sashimi, and the whole of cabbage rolls and steak for the reproduction pattern. At 7 cm/s, three participants reported that they felt as if they had swallowed some kind of solid food. In the horizontal pattern, subject E commented that at 1, 3, and 5 cm/s, and subject F, G commented that at 3 cm/s it felt like swallowing solid food. Subject E answered that at 1cm/s he swallowed potatoes in Japanese starchy curry rice and normal-sized solid

TABLE 8. List of foods and beverages that participants felt like they were swallowed in the vertical pattern questionaire comments.

	Subject				
	E	F	G	I	K
1cm/s	Potatoes in curry Regular size food	Something sticky Phlegm during a cold			something thick
3cm/s	Large size food	solid food	quickly swallowing solid food	food that hard to swallow	
5cm/s	Lotus root Cucumber Sausage	dry swallow		sparkling water	
7cm/s				food that hard to swallow thin liquid	
Random		gulp wator			

TABLE 9. List of foods and beverages that participants felt like they were swallowed in the horizontal pattern questionaire comments.

	Subject				
	E	F	G	I	K
1cm/s	drinking straight from a bottle sherbet			Something sticky	
3cm/s	thicky noodle soup Large meat corn potage			Sparkling water	
5cm/s	Steak runny liquids Thin and soft noodles	dry swallow		little thick water	
7cm/s	Sashimi of Tuna		solid food		Large size food
REPL	cabbage roll Steak		dry swallow	dry swallow	

foods, at 3cm/s a large food, and at 5cm/s a whole lotus root, cucumber and sausage. As can be seen, as the speed of subject E increases, it changes to become feeling like swallowing larger solid food. For subject F, at 3cm/s, he felt it was solid, but at speed 1cm/s, he felt it was a viscous liquid, indicating that the food hardness of the comment increased as the speed increased. As can be seen from these results, it was suggested that the nature of the food or drink that was perceived as swallowed could be changed by changing the speed and the tape pattern of the device. These reasons include the fact that the size, hardness, and viscosity of the food or drink swallowed affect the amount and speed of hyoid bone movement. In previous studies in anatomy and medicine, it has been reported that hyoid bone movement is increased when swallowing a hard food mass [17]. In addition, it has also been reported that the larger the food mass, the greater the amount of movement [18], [19]. These studies suggest that the size and hardness of food and drink are positively correlated with the amount of movement of the hyoid bone. In Grutio, there is no change in the amount of movement, only a change in speed, but there is a change in the perceived hardness and size of the swallowed object depending on the speed. This may be due to an illusion of the amount of change since at higher velocities the traction is for a shorter time and is perceived as a shorter distance, while at lower velocities the traction is for a longer time. This is consistent with the changes in the comments of subject E in the parallel arrangement pattern. Similarly, a previous study [20] reported that an increase in food/drink viscosity leads to a decrease in swallowing speed. Subject E also commented that there was a similar decrease in velocity and increase in viscosity, and subject K also commented that it was a sloppy liquid at 1 cm/s in the vertical configuration. These results suggest that measuring the speed of the real object to some extent and presenting movements that match it is effective in reproducing the sensation of swallowing, as supported by the strong positive correlation between Q1, Q2-Q3. In addition, the subject G, I commented that he felt as if he were dry-swallowing in the pattern that reproduced the fastest speed. Saliva is low in viscosity and volume, which is a characteristic of fast swallowing, and is consistent with previous studies. However, there are comments that solids and large objects were swallowed even at the faster speeds of 7cm/s and the parallel arrangement of the reproduction patterns. (Subject I: 7cm/s, Subject GI reproduction pattern) The reason for this is that in the present experiment, the swallowing motion, which is voluntary in nature, was given passively. When a person swallows a large piece of food, he or she feels a catch or blockage in the throat, followed by a feeling of release. We believe that the sudden and fast movements of the device may have caused the user to feel such a sensation.

Limitations of this study include the way the device is mounted, the user's posture during operation, and the importance of calibration. In the current system, the actuator and control system are mounted on the chest, and the effect of this position can be seen. For example, if the user is a man with extremely well-developed pectoral muscles or a woman with a large chest, the traction position of the device will move forward. As a result, the direction of traction changes from downward to forward. Also, in actual operation, there are various postures when eating and drinking. However, Grutio is currently designed for sitting up straight, and it would be difficult to use it for actual eating and drinking. To solve these problems, it is necessary to improve the Grutio so that it can be installed in a position where the position of the throat does not change drastically due to postures, such as the neck and shoulders. There is also the problem of calibration. In our experiments, we found that we could make the swallowing sensation more stable by performing various calibrations. However, the current system is not very efficient because it requires manual adjustment of the attachment position and speed. For practical use, it would be desirable to design and implement an automatic calibration system and a skin movement system using something other than tape, such as a silicon plate.

VI. CONCLUSION AND FUTUREWORKS

In this paper, we proposed the Grutio, a device that presenting the sensation of swallowing by pulling and moving the skin of the throat in the same way as the actual swallowing motion. To evaluate the device, we conducted a three-day evaluation experiment with each of nine participants. As a result, six of the nine participants had an effective pattern of swallowing sensation that was stable for three days, and they were able to feel sufficient sensation. The remaining three participants also succeeded in feeling a sensation of swallowing at least 3 times, and all participants were able to feel a sensation of swallowing. In addition, there was a positive correlation between the subjective approximation of the movements and the sensation of swallowing felt by the subject, suggesting that more realistic movements can be presented to more effectively present the sensation of swallowing. Therefore, by adding a calibration procedure to adjust the speed and amount of traction for each user, Grutio can present more effective the sensation of swallowing without actually eating or drinking anything. Up to now, among the sensations in eating, the swallowing sensation has not been reproduced, but by applying this device, most of the sensations in eating can be reproduced, and this research has contributed to the realization of complete VR eating and drinking.

The results obtained from the free-description comments also suggested that, just as hardness, softness, and viscosity affect swallowing speed and hyoid bone movement in actual swallowing, the speed at which the device is operated can change the nature of what is swallowed and made to be felt. As the speed of the device decreased, the participants felt that the viscosity and size of what they thought they had swallowed changed. This could be used to realize a swallowing texture by superimposing it on the actual swallowing of something or to enhance the reality of food and drink in VR eating and drinking without actually taking something in the mouth.

Limitations of Grutio include the way the device is mounted, the user's posture during operation, and the importance of calibration. In the future, we will need to work on how to attach the device, how to move the skin, and how to build an automatic calibration system. In addition, as part of FutureWorks, we would like to present swallowing sensations in an immersive environment equipped with HMDs, olfactory displays, and electric gustatory senses, and investigate the effects on the overall reality of eating and drinking. and We would like to investigate the relationship between presentation speed and swallowing sensation using drinking water of different viscosities for comparison.

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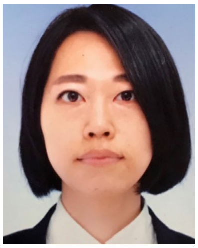

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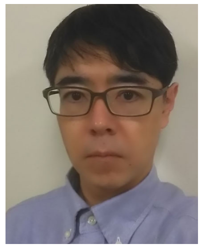

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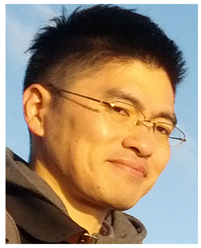

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