Augmentation of Toothbrush by Modulating Sounds Resulting from Brushing

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Abstract. Brushing teeth is a daily habit to maintain oral hygiene, including the maintenance of oral cleanliness and prevention of caries and periodontal disease. However, tooth brushing is often not carried out correctly or forgotten because the task is boring. Although several works have contributed to improving brushing performance and motivation, the feedback seems to be very remote from the brushing itself, i.e., not intuitive. In this study, we establish two objectives to deal with these issues. The first is not to present information on a visual display, but to augment the ordinary tooth brushing experience consisting of haptic and auditory sensations, while the other is to design the modulation so that users feel as if their teeth are gradually becoming cleaner, thereby providing the necessary motivation. To achieve these aims, we propose a novel approach to augment the tooth brushing experience by modulating the brushing sounds to make tooth brushing entertaining in an intuitive manner. A microphone embedded in the toothbrush records the brushing sounds, which are presented to users after being modified by a PC. In the experiment, we demonstrate that increasing the sound gain and manipulating the frequency can control the overall impression of brushing by giving a sense of comfort and accomplishment.

Keywords: Augmented reality, sound effect, tooth brushing.

1 Introduction

The purpose of personal oral hygiene, which is generally carried out using a toothbrush, is the maintenance of oral cleanliness and prevention of caries and periodontal disease. Ideally, brushing should be done frequently and correctly to achieve the desired effect. However, brushing is often not carried out correctly or simply forgotten because the task is boring. Thus, there are two main issues with current tooth brushing: one is the lack of motivation, while the other is using the incorrect technique for brushing. To deal with these issues, a wide variety of applications have been proposed in research and development studies on consumer goods.

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One of the reasons for the lack of motivation for tooth brushing is the negative reward; i.e., people brush their teeth so as NOT to get caries, which seldom motivates them. Therefore, if we can change this to a positive reward, they would be more highly motivated. Nakajima et al. proposed the virtual aquarium where tropical fish become active and produce eggs if the users brush their teeth [1]. Hasbro released Tooth Tunes, which consists of a small pressure sensor to detect contact between the bristles and teeth and a bone conduction speaker to play a music clip during contact [2]. These works contribute to motivating users by providing alternative rewards.

To guide the correct way to brush, the SmartGuide has been released by Oral-B. This divides the teeth into four sections and counts brushing actions on a liquid crystal display (LCD) showing how many times the users have brushed their teeth and still should brush them [3]. Chang et al. proposed the Playful Toothbrush, which encourages children to brush their teeth correctly by tracking the toothbrush and identifying where they are brushing [4]. In addition, the Playful Toothbrush feeds back a visual and auditory reward according to the correct brushing performance, thus motivating children to brush their teeth.

It is clear that these works succeed in improving the way we brush (i.e., correctness) and providing sufficient motivation (i.e., frequency). On the other hand, the quality of feedback is an issue for the following reason. Although the previous work presented cues with visual display or music to guide correct tooth brushing, the feedback seems very remote from the brushing itself. Thus, users are forced to understand what the cues mean. To deal with this issue, an approach that provides intuitive cues for correct tooth brushing, as well as motivating the users, is required.

In this study, we propose a novel feedback approach that makes tooth brushing entertaining in an intuitive way. To achieve this goal, we consider two objectives. The first is not to present information on a visual display, but to augment the ordinary tooth brushing experience consisting of haptic and auditory sensations. We believe that modulation of real sensations is the simplest, yet still a robust way of presenting information intuitively. The other is to design the modulation so that the user feels as if his/her teeth are gradually becoming cleaner, thereby providing motivation.

This paper begins with a review of prior work on sensory (haptic and auditory) presentation in the oral cavity. Then, we describe our proposed approach, which modulates the sounds resulting from brushing teeth to provide an increasingly comfortable sensation (i.e., intuitive cues) that motivates the users. Thereafter, we present a pilot study to demonstrate the efficacy of the proposed approach. Finally, the paper ends with a discussion of our future work based on the experimental results and our conclusions.

2 Related Work

A number of works studying sensory presentation in the oral cavity were carried out mainly to simulate or enhance the eating experience. Since the tooth brushing experience is mainly derived from haptic and auditory sensations, we focus on previous work related to these two sensory presentations in the oral cavity.

2.1 Presenting Haptic Sensation

Iwata et al. proposed the Food Simulator, which is a haptic interface that generates a force on the users' teeth simulating food texture by means of a one degree-of-freedom (DoF) mechanism [5]. They successfully presented food texture as well as chemical taste. However, applying a force feedback mechanism to a toothbrush is not practical because a multiple DoF force feedback device is required, thus leading to higher cost.

Hashimoto et al. proposed the Straw-like User Interface (SUI), which is an audio-tactile interface that presents the vibration and sound resulting from suction with a straw [6]. They demonstrated that the SUI can simulate the experience of drinking a wide variety of things. However, tooth brushing produces vibration and sound that would mask additional vibration. Thus, it is difficult to directly modulate the haptic experience of tooth brushing.

2.2 Presenting Auditory Sensation

Zampini and Spence found that the crisper and fresher potato chips were perceived as being, either the louder the overall sound level rose or the higher the amplified frequency of the biting sound became [7]. Koizumi et al. employed and developed this effect to augment the experience of biting and chewing foods by synchronizing the jaw action [8].

These techniques can be used to modulate the sensation in the oral cavity and can easily be realized using auditory interfaces, such as a microphone and headphones, without complicated mechanisms like haptic interfaces. Thus, employing these techniques is practical.

Furthermore, in the field of cross-modal research, it is well-known that the haptic perception of a variety of surface textures (including outside the oral cavity) can be changed by modulating the auditory cues resulting from exploration [7][9-11]. For example, Jousmäki and Hari demonstrated that sounds that are exactly synchronous with hand-rubbing modify the resulting tactile sensation (the parchment-skin illusion) [9]. The palm is perceived as being smoother and dryer, like the surface of paper, when the high-frequency component of the rubbing sound is amplified or the overall sound level is increased. We believe that this cross-modal phenomenon enhances the modulation effect.

3 Proposed Approach

From previous work on modulating sounds resulting from exploration, we believe that the technique can be applied to a toothbrush by simply embedding a microphone in the toothbrush and presenting modulated brushing sounds by applying audio filter (e.g., band pass filter).

By considering previous work, amplifying the low-frequency component evokes a moist (or sticky) and rough feeling on the teeth. This would make the users feel uncomfortable (Fig. 1-a). On the contrary, amplifying the high-frequency component.

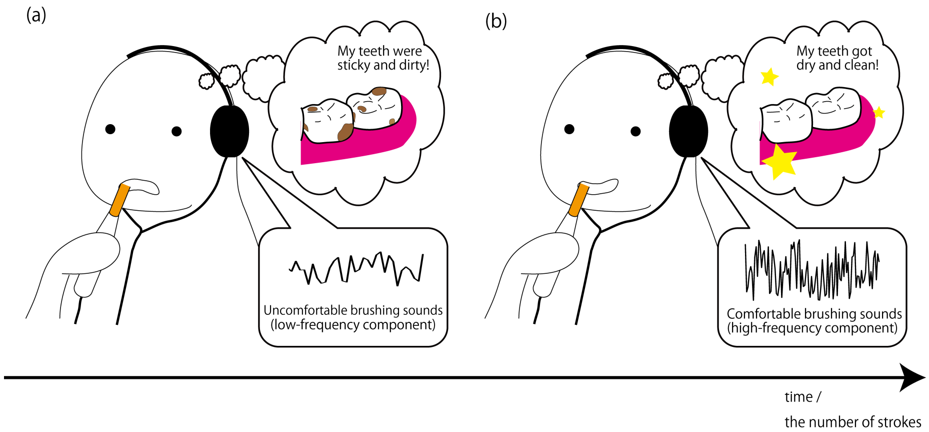

Fig. 1. The proposed approach: (a) the low-frequency component would evoke moisture (or sticky) and rough feeling on tooth (uncomfortable feeling). (b) the high-frequency component of brushing sounds would evoke dry and smooth feeling (comfortable feeling).

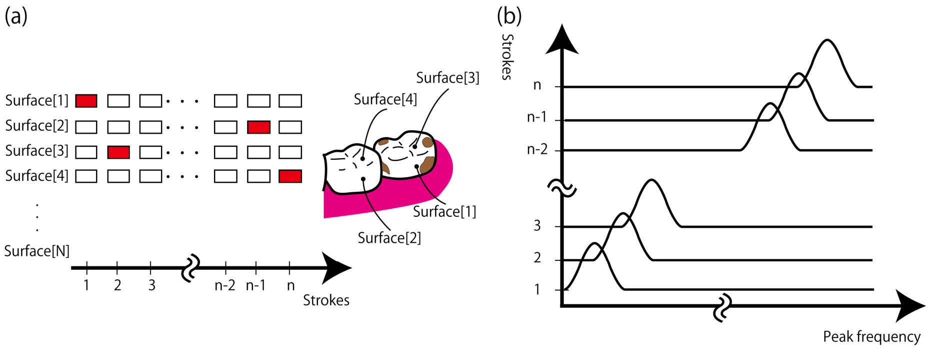

Fig. 2. Associating the proposed approach with a toothbrush tracking system, such as in [4]: (a) the system counts the number of strokes on each tooth, and (b) the peak frequency of the band pass filter is determined based on the count

of brushing sounds evokes a dry and smooth feeling on the teeth, thus making the users feel comfortable (Fig. 1-b).

We believe that it is possible to provide intuitive cues for users by controlling the level of comfort of sensations, allowing the users to be aware of the condition of their teeth; i.e., clear or dirty. Since the modulating sounds are derived from the original brushing sounds, this technique achieves our first objective; i.e., to augment the ordinary tooth brushing experience (intuitiveness). In addition, it would be possible to enhance the feeling of accomplishment by designing sound manipulation, since users would intuitively know the progress of cleaning, thereby addressing our second aim of motivating the users.

Furthermore, by associating the technique with a toothbrush tracking system, such as in [4], it is possible to present the condition of each tooth. The system counts the number of strokes on each tooth (Fig. 2-a) and modulates the sound to evoke either a comfortable or uncomfortable feeling based on the count (e.g., the peak frequency of the band pass filter is higher when the count increases, Fig. 2-b). For example, if a tooth has been brushed well, the system provides comfortable brushing (high-frequency) sounds (at Surface[2] and Surface[4] in Fig. 2); if not, it provides uncomfortable (low-frequency) sounds (at Surface[1] and Surface[3] in Fig. 2). This would enable users to know which teeth have been brushed enough and which have not. In other words, the user can intuitively know how many times and which teeth they should brush merely by brushing their teeth.

4 Experiment

To investigate whether our proposed approach can modulate the impression of tooth brushing, we conducted an experiment in which participants were asked to evaluate the feelings of comfort and accomplishment from brushing. The former feeling is mainly related to creating intuitive cues, while the latter is related to how the design motivates the users.

4.1 Setup

Toothbrush. We created a toothbrush with an interchangeable brush (ASIANETWORKS Co., Ltd.) to consider the sanitary issue, as shown in Fig. 3. The toothbrush has a length of 160 mm, with weight 20 g. Fig. 4 shows the internal configuration of the handle, which is made of acrylonitrile butadiene styrene (ABS) resin and contains a microphone (capacitor microphone, WM-61A, Panasonic Co.) to record brushing sounds, and a force sensor (miniature load cell, LMA-A-5N, Kyowa Electronic Instruments Co., Ltd.) to measure grip force. The microphone is attached to the central core, which connects to the brush, thus allowing brushing sounds to be recorded directly. The force sensor is fixed beneath the bump in the handle.

Recorded sound is sent to the microphone jack of a PC. The signal of the force sensor is also sent to the PC via a microcontroller (Arduino Duemilanove). These two signals are processed to provide auditory cues as described in the following section.

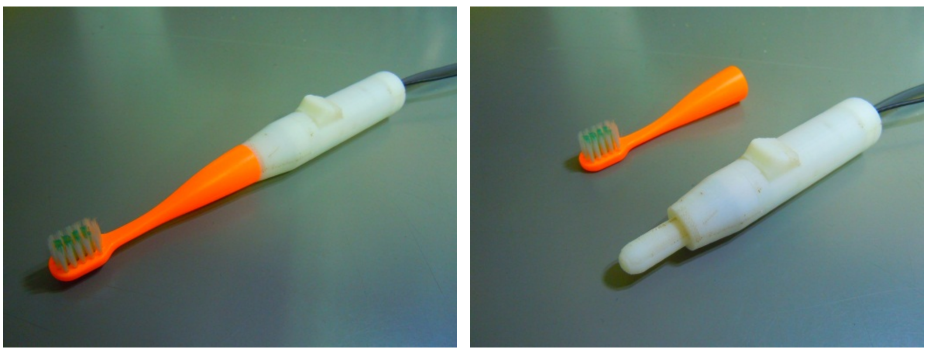

Fig. 3. Toothbrush used in the experiment

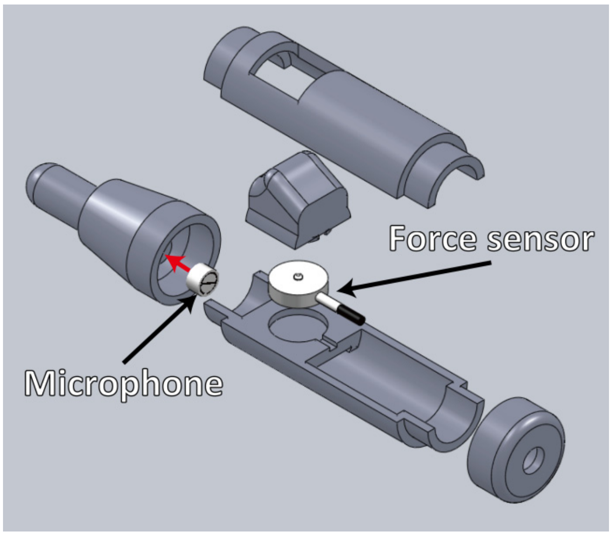

Fig. 4. Internal configuration of the handle of the toothbrush containing a microphone and a force sensor

Sound Processing. We used Max (version 6.0, Cycling '74) as the sound processer. For the brushing sound feedback, we used a band pass filter because this seemed to be the best filter to modulate sensation and express a wide variety of experiences in a preliminary investigation comparing a high pass, low pass, and band pass filter. We prepared five peak frequency conditions (500, 1000, 2000, 4000, and 8000 Hz) with a constant Q value (1.0). In addition, we prepared a non-filter condition as the control condition.

As indicated in previous work [7][9][10], the overall sound level affects the perception. Thus, we investigated three sound level conditions (-20, 0, and +20 dB). For the default sound level, i.e., the non-filter and 0 dB condition, the loudness of sounds was set at approximately 75 dB (A) using a sound level meter (digital sound level meter, TM-102, Sato Shouji Inc.). For the other conditions, the sound levels were set by Max.

In the experiment, the amount of force applied to the toothbrush affected the feelings of comfort and accomplishment from brushing. To avoid this, a beep sound was emitted if the grip force exceeded 20 N.

Environment. As shown in Fig. 5, the participants sat on a chair in front of a table and next to a sink, with headphones (sound-isolating earbud headphones, EX-29, Direct Sound Headphones Inc.) on their head. The toothbrush, an LCD, a ten-key keypad, a cup of water, and potato chips were placed on the table.

Fig. 5. Setup for the experiment

4.2 Procedure

The participants were instructed how to brush their teeth. They gripped the toothbrush in their right hands similar to holding a pen, with their thumbs on the bump of the handle (i.e., on the force sensor). They were instructed not to grip too tightly to avoid the beep sound (i.e., less than 20 N). They were asked to brush the buccal surface of the left upper second and third molars using five strokes and employing the Bass method [12].

In each trial, the participants first brushed their teeth under the standard condition (i.e., non-filter and 0 dB). Next, they brushed their teeth under a comparative condition. Then, they rated the subjective sensation of the comparative condition, such as feelings of comfort and accomplishment, using the ten-key keypad according to the analog scales on the LCD. The scales included 100 divisions with semantic anchors at either end of the scale bars. The left end (i.e., 0) of the comfort / accomplishment feeling bar represented “uncomfortable” / “not brushed at all”, while the opposite side (i.e., 100) represented “comfortable” / “brushed well”. The participants were asked to rate each of these two scales when the standard condition was rated 50. There was no limit on the time taken to respond.

Each participant performed this evaluation task 54 times; i.e., (five peak frequency conditions + one non-filter condition) × three sound gain conditions × three repetitions. Comparative conditions were randomly presented and the participants were unaware of the parameters.

Before the trials, the participants practiced this procedure a few times without the headphones. Every nine trials, they ate a piece of potato chip, chewing them on the left side to keep their teeth dirty. They were allowed to rinse their mouths freely during the experiment.

Seven participants—four men and three women—aged between 22 and 25 (mean = 22.9; SD = 1.2) took part in the experiment. All participants were right-handed.

4.3 Results

Comfort Feeling. The results of the feeling of comfort for the three sound gain conditions with respect to the six frequency manipulation conditions are shown in Fig. 6. A two-way within-participants repeated-measures analysis of variance (ANOVA) was performed on the data. The within-participants factors were Frequency Manipulation (i.e., peak frequency; 500, 1000, 2000, 4000, and 8000 Hz and the control condition) and Sound Gain (i.e., -20 dB, 0 dB, and 20dB).

The effect of Sound Gain was significant ($F(2, 12) = 4.51$, $p < 0.05$). The rating score for comfort was higher under the 0 dB condition (mean (M) = 52.4; standard deviation (SD) = 2.6) than either the -20 dB (M = 44.6; SD = 1.5) or 20 dB condition (M = 40.0; SD = 9.1).

The interaction effect between Frequency Manipulation and Sound Gain was significant ($F(10, 60) = 3.10$, $p < 0.01$). Simple main effects were found for Sound Gain under the 4000 Hz ($F(2, 12) = 4.69$, $p < 0.05$) and control conditions ($F(2, 12) = 7.68$, $p < 0.01$) and for Frequency Manipulation at the 20 dB level ($F(5, 30) = 4.69$, $p < 0.01$), which imply that the effect of Frequency Manipulation had a greater influence on comfort at 20 dB than at the other Sound Gain levels; i.e., -20 dB or 0 dB.

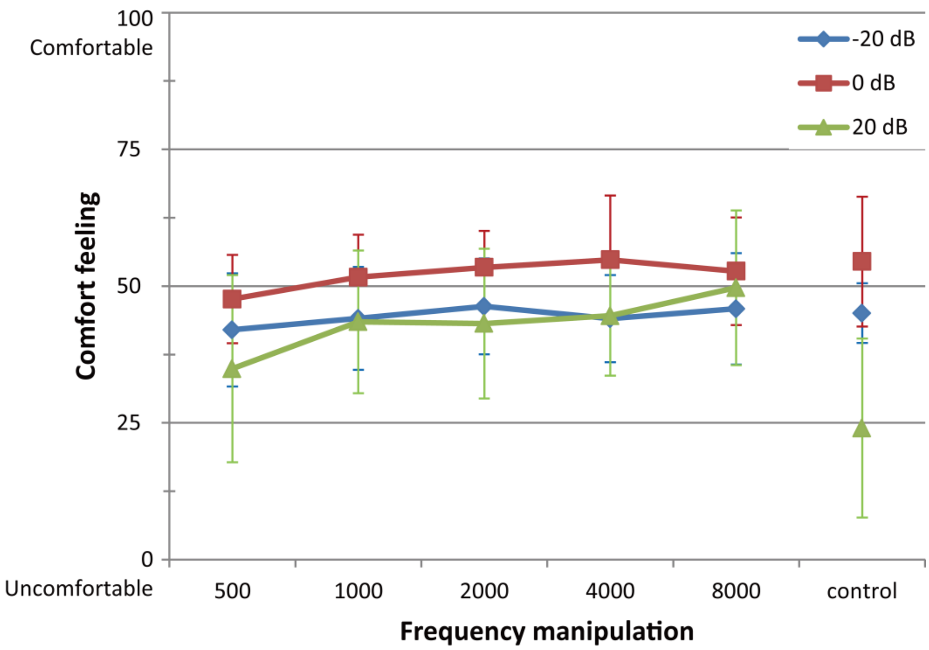

Fig. 6. Results of the experiment. Mean values of the comfort feeling for the three sound gain levels with respect to the six frequency manipulation conditions. Error bars denote standard deviation.

Accomplishment Feeling. The results for the accomplishment feeling for the three sound gain levels with respect to the six frequency manipulation conditions are shown in Fig. 7. An ANOVA was performed on this data similar to that for the comfort feeling data.

The effects of Frequency Manipulation ($F(5, 30) = 13.12$, $p < 0.01$) and Sound Gain ($F(2, 12) = 21.33$, $p < 0.01$) were significant. Furthermore, the interaction effect between Frequency Manipulation and Sound Gain was also significant ($F(10, 60) = 6.22$, $p < 0.01$). Simple main effects were found for Sound Gain under the 2000 Hz ($F(2, 12) = 5.12$, $p < 0.05$), the 4000 Hz ($F(2, 12) = 9.11$, $p < 0.01$), the 8000 Hz ($F(2, 12) = 18.33$, $p < 0.01$), and the control conditions ($F(2, 12) = 29.07$, $p < 0.01$) and for Frequency Manipulation under the 20 dB level ($F(5, 30) =25.12$, $p < 0.01$), which implies that the effect of Frequency Manipulation had a greater influence on the accomplishment feeling than for the other Sound Gain levels; i.e., the -20 dB and 0 dB levels, as well as the comfort feeling.

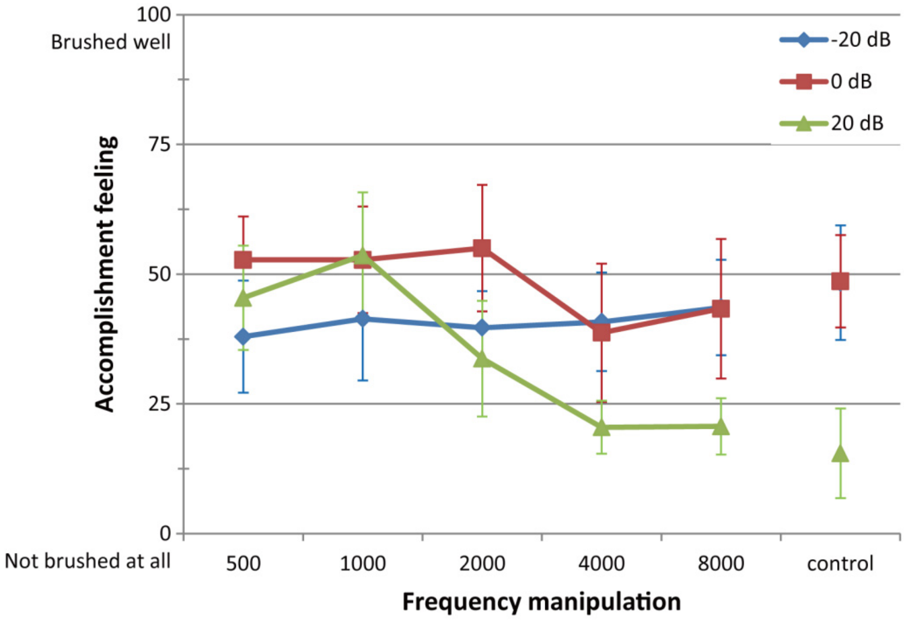

Fig. 7. Results of the experiment. Mean values of the accomplishment feeling for the three sound gain levels with respect to the six frequency manipulation conditions. Error bars denote standard deviation.

Correlation between Two Scales. We plotted all 378 pairs of scores on a two dimensional graph (with the x- and y-axes denoting the feelings of comfort and accomplishment, respectively) to investigate the coefficient of correlation between the two scales by applying linear approximation. As shown in Fig. 8, there was almost no correlation ($R^2 = 0.2167$), which implies that the participants distinguished two scales and a comfortable feeling did not always induce a feeling of accomplishment and vice versa.

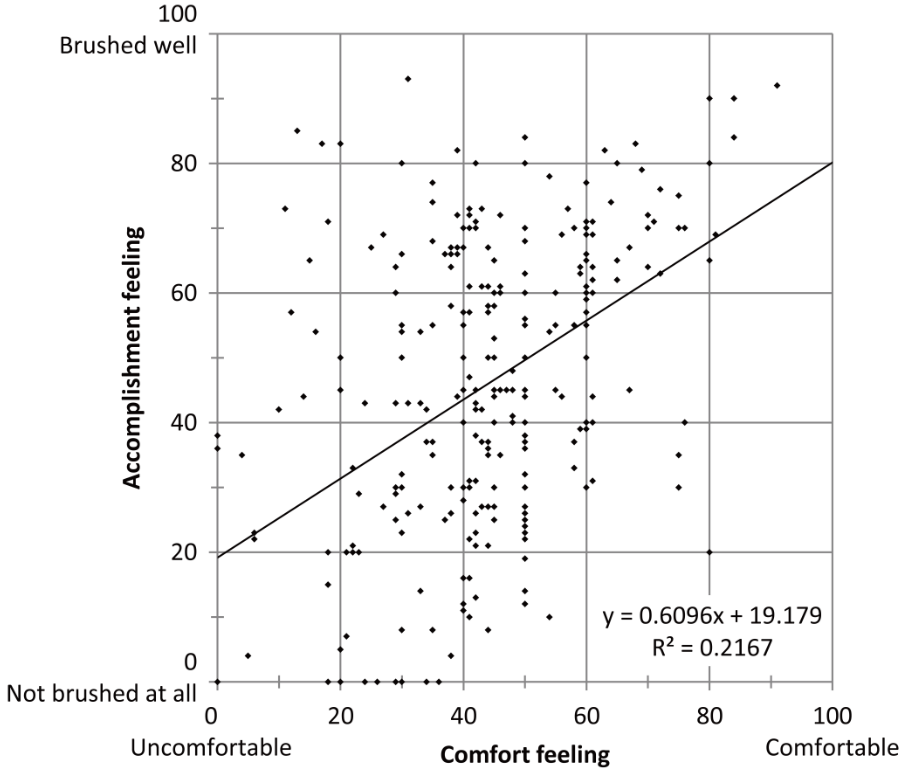

Fig. 8. Results of the experiment. The correlation between the two scales, that is, feelings of comfort and accomplishment.

4.4 Discussion

The results demonstrated that our proposed approach could modulate both comfort and accomplishment feelings by increasing the sound gain and manipulating frequency. Thus, it is possible to provide intuitive cues (i.e., comfortable versus uncomfortable) and to provide motivation by controlling the feeling of accomplishment.

After the experiment, four of the participants reported that the louder the sounds became, the higher the feeling of accomplishment was. On the other hand, another participant said that too loud a brushing sound evoked a feeling of insufficiency, because they felt as if they had not brushed their teeth by themselves, which probably explains the low rating of accomplishment feeling at 20 dB condition. Furthermore, two of the participants reported that some conditions were so loud that they felt uncomfortable, which probably explains the low rating of comfort feeling at 20 dB condition. Based on the comments that the 20 dB condition was felt to be too loud for some participants, we should consider an amplification level between 0 dB and 20 dB in future studies.

At the 20 dB level, on the other hand, frequency manipulation had a greater influence on both feelings as shown by the simple main effect. Regarding the comfort feeling, the participants felt comfortable when the higher band pass filter was applied. For the feeling of accomplishment, the participants felt an insufficiency feeling when the higher band pass filter was applied, which seemed to peak at around 1000 Hz.

At the -20 dB and 0 dB levels, on the contrary, frequency manipulation did not influence either feeling. One of the possible reasons for this at the -20 dB level is that the sound gain was so soft that the participants could not perceive the change in frequency. Even at the 0 dB level, the sound gain might not have been enough to perceive the change because applying the band pass filter decreases the overall sound level.

There was no correlation between the feelings of comfort and accomplishment. This tendency was especially notable at the 20 dB level as mentioned before. By taking into consideration the comments from the participants, the comfortable feeling seems to come from cues implying that the teeth have been cleaned and it is not necessary to brush them anymore. This feeling may be induced by presenting high-frequency components of the brushing sound that evoke a dry and smooth surface sensation as described in the parchment-skin illusion [9]. On the contrary, the score for the feeling of accomplishment decreased because the participants felt that they did not have to brush their teeth anymore; i.e., their teeth had already been cleaned. For the 1000 Hz condition, on the other hand, the participants felt something sticky like food debris on their teeth. Thus, they felt uncomfortable and dislodging this by brushing induced a sense of accomplishment. However, for the 500 Hz condition, the score for accomplishment shows a decreasing tendency. This could be because the participants perceived their teeth or the bristles as being something too soft to identify. Thus, they felt uncomfortable and no longer imagined that they were dislodging something. Furthermore, under the non-filter condition, both scores decreased significantly, confirming our previous discussion; i.e., too loud sounds induced an uncomfortable and insufficient feeling.

Two of the participants reported that the microphone picked up sound irrelevant to brushing, such as environmental sound and the sound produced by the electric cord touching the table. One solution is to employ a highly directional microphone or an accelerometer instead of the current omni directional microphone.

After the experiment, all participants reported that the experience of hearing their own brushing sounds was interesting and modulating the sounds somehow altered their tooth brushing experience.

5 Conclusion

This paper first addressed the current issue with tooth brushing, namely the quality of feedback. To deal with this issue, we established two objectives:

1. not to present information on a visual display, but to augment the ordinary tooth brushing experience; and
2. to design the modulation so that the user feels as if his/her teeth are gradually becoming cleaner.

Next, we proposed a novel approach to augment the tooth brushing experience by modulating the brushing sounds to make tooth brushing entertaining in an intuitive manner. A microphone embedded in the toothbrush records the brushing sounds, which are then modified by a PC and presented to users. In the experiment, we demonstrated that increasing the sound gain and manipulating frequency modulated the tooth brushing impression, in terms of feelings of comfort and accomplishment. However, it is still unclear what the optimal sound gain, frequency, and sound filter are. Thus, investigating these parameters is one of our future works.

In the future, we intend studying the efficacy of the presenting condition of each tooth (i.e., clean or dirty) through the proposed technique (as illustrated in Fig. 2) in conjunction with a toothbrush tracking system, such as that in [4]. Furthermore, we would like to conduct a long-term user study to verify whether our proposed approach can provide motivation and is compatible with daily life.

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