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Development Report:

Development of the Second Prototype of an Oral Care Simulator

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Oral care is crucial to preventing diseases and maintaining the quality of life of elderly people. To create an effective training environment for nursing students, we developed a second prototype of an oral care simulator that can guide and record oral care practices. The simulator has three components: (1) a dentition model with pressure sensors, (2) a microcomputer to record signals, and (3) software for visualization. We proposed a novel mechanism to detect brushing behavior using pressure sensors and developed software to visualize the records of oral care practice. We calibrated the system to estimate the weights applied in the dentition model using a brush and verified that the calibration increased the accuracy of the estimation.

Keywords: oral care, simulator, nursing education, 3D printing, interactive system

1. Introduction

Oral care includes activities that clean one's mouth by removing plaque and biofilms using sponge brushes or toothbrushes. Pneumonia, which is a widely observed infection, can be caused by the aspiration of oropharyngeal bacterial pathogens into the lower respiratory tract [1]. Yoneyama et al. reported that oral care can prevent aspiration pneumonia [2]. According to Furuta and Yamashita, toothbrushing can aid in improving oral hygiene and oral functions by increasing the salivary flow rate [3]. Thus, oral care can be expected to improve oral functions such as the swallowing reflex. Therefore, oral care has an important function in the prevention of diseases and improving quality of life, particularly for elderly people [3]. In Japan, education for oral care is not sufficient in nursing schools. Haresaku et al. reported that 57.4% of first-year nursing students who participated in their study had a negative willingness to practice oral health care after obtaining their professional qualifications in the future [4]. In nursing education, students learn oral care skills by applying them to a simulated model or the mouth of other students, as using actual patients results in safety or ethical concerns. However, this process cannot provide direct feedback from teachers who are experts in oral care because the number of students is significantly higher than that of teachers.

The aim of this study was to develop a simulator that enables nursing students to learn practical oral care skills. Simulation-based education for nursing students uses a variety of simulators that enable students to learn how to perform nursing skills to patients with various symptoms. The adoption of simulators has many advantages such as immediate feedback, repetitive practice, adjustable difficulty, and individualized learning [5]. A debriefing session often occurs in simulation-based learning. This prompts students to examine their practices and check whether they can achieve their goals. Through a systematic review, Levett-Jones and Lapkin concluded that debriefing contributes to effective learning and should be included in all simulation learning experiences [6].

For a more effective debriefing session, we consider that simulators should be able to record the practices of students. The oral care simulator we developed enables students to evaluate their practice easily through recording and visualization functions. According to Jansson et al., oral care practices using simulators are not effective if they are performed only once, and repetitive practice is required to acquire practical skills [7]. Recording and visualization can contribute to repetitive practice and the acquisition of practical oral care skills. The target practice of our study was brushing with a toothbrush and sponge brush, which are widely used in oral care.

The summary of the current scenario is as follows.

- In general nursing education, simulators that can provide functions for real-time feedback, repeated practice, changing the difficulty level, and individual learning are used.
- In the domain of oral care, there are no simulators that can record and visualize practices, and practices are not recorded.

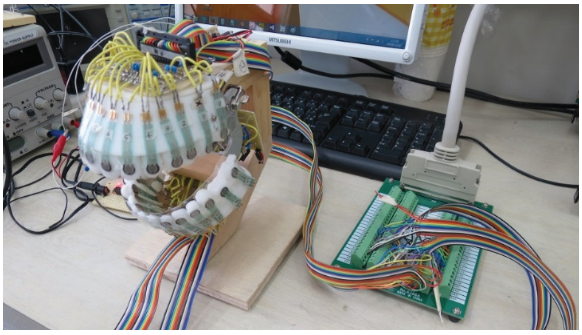

Fig. 1. First prototype of an oral care simulator [8].

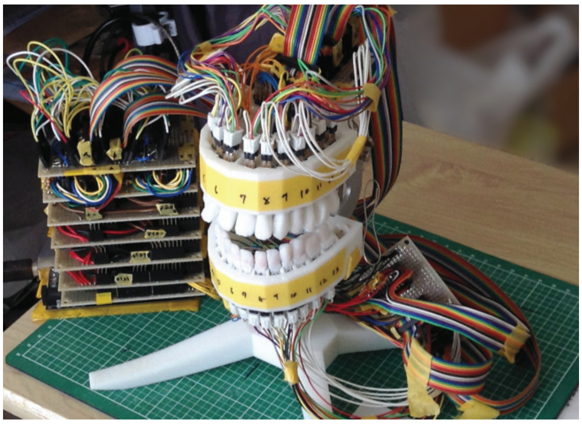

Fig. 2. Second prototype of the oral care simulator.

This research aimed to solve the latter scenario. We developed the first prototype of an oral care simulator [8] (**Fig. 1**). The simulator had a 3D-printed dentition model with pressure sensors attached to the surface of the teeth directory. We used an external function board for the analog-to-digital (A/D) conversion of the sensor signals. We also developed software for recording oral care practices. The first prototype had several problems, such as inaccurate detection of brushing behavior and unrealistic appearance as the teeth were too large owing to the sensing method used. To solve the problems of the first prototype, we developed a second one (**Fig. 2**). This paper describes the improvements in detail.

2. Related Studies

The oral model is the widely used simulator for oral care in nursing education (M89 Oral Care Simulator, Kyoto Kagaku Co., Ltd.) [a]. This model has an oral cavity with teeth and a tongue similar to that of actual humans and enables students to practice oral cleaning. The model does not have any functions to record students' practices.

For training devices in nursing, Murakami et al. evaluated the effectiveness of the use of vascular access imaging devices for peripheral intravenous line placement by recent nursing school graduates [9]. Komizunai et al. developed an endotracheal suctioning simulator that can exhibit vital reactions in a patient, including facial expression changes [10].

Some dental schools use 3D printing technology to create simulators for education. Kröger et al. developed a dentition model with gingiva through a direct 3D surface scanning of the oral cavity and 3D printing [11]. They obtained preferable opinions from students who joined their hands-on course using their 3D printed models. Reymus et al. created replicas of actual human teeth for endodontic education [12]. They digitized actual teeth using cone-beam computed tomography and printed the data using 3D printers. They scanned the printed teeth to measure the absolute deviation from the original data (this can measure trueness) and deviation from the other data (measure accuracy). They concluded that their production process was suitable for endodontic training. We used 3D computer-aided design and 3D printing technology to develop the dentition model of our simulator.

Related to the evaluation of oral care practice, Schlueter et al. developed systematics for toothbrushing behavior [13]. The index they defined can evaluate one's toothbrushing behavior numerically in terms of (1) completeness, (2) isochronism, and (3) consistency. They verified their index using synthesized and clinical observation data. They observed that the calculated indices increased after the subjects learned other brushing systematics.

Some studies used clinical virtual simulators (CVSs). Padilha et al. examined the attitudes of nursing students toward CVSs and reported that they are highly motivated to use CVSs [14]. Harrington et al. developed and evaluated the world's first medical decision-making simulator on the Oculus virtual reality platform [15]. Keys et al. developed a virtual simulation game for nursing resuscitation education that can simulate the resuscitation procedure through multiple-choice critical thinking questions [16]. Our prototypes did not adopt the methods of virtual reality or gaming. This is because we aimed to confirm the validity of our system in training a user's physical skills.

Some studies were partially related to ours but had different objectives. Mitani and Muramatsu developed a tongue model for the mealtime assistant simulation model [17]. Mealtime assistance is for elderly persons with swallowing disorders. Their aim was to provide a training environment for nursing students using their simulator, which can detect a spoon that is inserted on the tongue of the model. Hanasaki et al. examined gender differences in toothbrushing by comparing self-brushing and brushing by dental hygienists using a 3D acceleration sensor and strain gauge attached to a toothbrush [18]. Huang and Lin developed a toothbrushing monitoring system using a brush and a wristwatch [19]. Their system recognized toothbrushing gestures using magnetic, inertial, and acoustic sensing signals. They focused on a brush and wristwatch for the detection of brushing behavior, but we focused on teeth as we did not aim to make changes to a brush. When a nurse or a caregiver performs oral care, they use brushes without modification. Ledder et al. examined the effects of brushing using toothbrush-

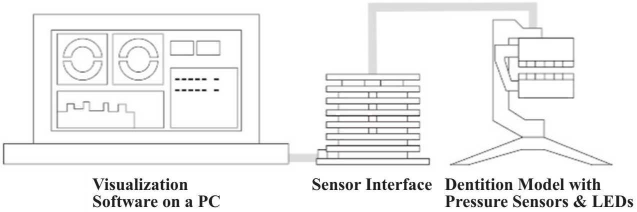

Fig. 3. Components of the second prototype.

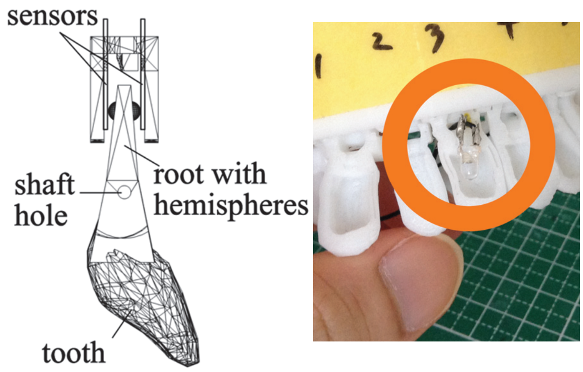

Fig. 4. Sensing unit (left) and LED in a tooth (right).

ing simulators [20]. The simulator was used for simulating toothbrushing against typodonts mechanically and not for training by humans.

In dentistry, studies have focused on measuring forces applied to teeth. Mencattelli et al. [21] developed a system to measure orthodontic forces applied on synthetic teeth using strain gauges and load cells. Midorikawa et al. [22] also developed a similar system using 6-axis sensors for 14 teeth of the mandibular jaw. Their aim was to measure orthodontic forces to design safer tools and to train dentists. Their systems required rod parts to convey forces from the tooth root to sensors, thus requiring spaces to place these parts. We avoided the use of such parts to assure spaces around the mouth as we focused on brushing. In brushing, a caregiver moves their hands around the patient's mouth; therefore, the same amount of free space as an actual mouth should exist. Hashimoto et al. [23] developed a system to measure forces to remove dental tartar to train dental hygienists using 3-axis force sensors. They only focused on a few teeth to be measured, and inferring from the size of the sensors, scaling up their method to all teeth is difficult. Our system can measure forces for all teeth using embedded pressure sensors.

The study most related to ours was that of Herath et al. [24]. They developed an anatomically correct oral care simulator for the training of nurses. Their simulator had a mandibular jaw with 16 teeth. They analyzed the stress on a tooth using the finite element method and used strain gauges to detect brushing stress. Our study adopted a different approach to theirs to achieve the same aim that was initiated from the same prototype [8].

3. Second Prototype

The second prototype of the oral care simulator is composed of three components (**Fig. 3**). The first is a dentition model. The teeth arrangements were created using a 3D printer (Afinia H800+: AFINIA 3D) and two pressure sensors (FSR400 Short: Interlink Electronics, Inc.) are embedded in each tooth. The second one is a sensor interface that consists of a multiplexor circuit and a microcomputer. The former selects a signal from the pressure sensors on the dentition model. The latter transfers these signals to a PC via a USB interface. The last one is the software we developed to visualize the recorded signals. The software was run on a Windows PC. In this section, we will explain the details of each component in comparison to those of the previous prototype. We call the first prototype "the previous model" and the second prototype "this model."

3.1. Dentition Model

In the previous model, pressure sensors were attached to the surface of the teeth directly. This caused inaccurate detection of brushstrokes because the brush was aimed to be "surface contacted," although the sensors assumed the stroke to be "point contacted." This meant that point collision did not occur because a brush has many bristles, which resulted in a quasi-surface contact. In this model, we included a root part to each tooth. The root has a small hemisphere on each labial (or buccal) and lingual sides. We created a structure that clips the root from the labial (buccal) and lingual sides, and pressure sensors were placed between the structure and the hemisphere on the root (**Fig. 4**, left). When a shaft is placed in the middle of the root, when force is applied on a tooth, the hemisphere on the root can push the pressure sensor on the same side of the direction of the force. Through this change, sensors on the surface of teeth are removed, resulting in the model with a more similar appearance to actual human teeth. We used a 3DCG software toolset (Blender: Blender Foundation) to design the dentition model.

In the previous model, the teeth were enlarged approximately twice the standard human teeth size calculated from the literature [25] to enable a pressure sensor with a diameter of 7.8 mm to be attached. In this model, we shrunk the teeth size to 1.6 times larger than actual teeth because we moved the sensors to the roots of the teeth. We designed a dentition model based on skull data by Askedall [b], which were also used in the previous model [8]. The data were licensed under the Creative Commons – Attribution-ShareAlike license [c].

3.2. Microcomputer

3.2.1. Guide by LEDs

In this model, we used the A/D conversion function of a single-board microcomputer (the equivalent model to ArduinoMega2560 R3: Arduino). In the previous model, we used a PCI Express peripheral I/O

Fig. 5. Ordering of the guide.

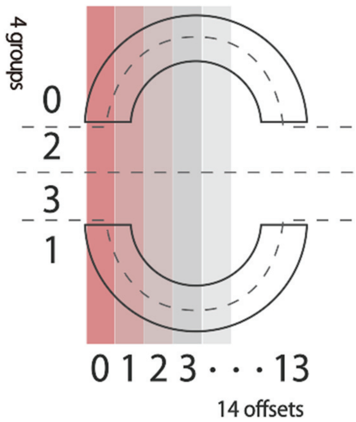

Fig. 6. Allocation of group/offset number.

board (AIO-163202F-PE: Contec Co., Ltd.) [d], which has 32 channels with simultaneous A/D conversion. With this device, we could monitor all the signals from the sensors on either the labial or lingual side of the dentition model simultaneously. Each side had 28 sensors. However, if we can assume that oral care training is conducted along with the procedures for safe oral care [26], the number of simultaneous monitoring procedures can be reduced by sequentially indicating brushing locations.

We embedded LEDs in each tooth of the dentition model to indicate the locations to be brushed by emitting light (**Fig. 4**, right, in the circle). We determined the light emission order according to the safe oral care procedure [26] and the opinion of oral care experts. The order is as follows (viewed from a user): (1) left molar, incisors, right molar on the maxillary jaw, (2) right molar, incisors, and left molar on the mandibular jaw (**Fig. 5**).

An ArduinoMega2560 R3 has 16 channel simultaneous analog inputs. We decided to use five channels for a target tooth and its four neighboring teeth. The reason is that a brush can be in contact with a target tooth and its neighbors. The target tooth was indicated by an LED emission, and sensor signals from the target and four neighboring sensors were recorded during emission.

The resolution of the A/D conversion was degraded from 16 bits (AIO-163202F-PE) to 10 bits (ArduinoMega2560 R3). With 10 bits of resolution, considering that the pressure-sensitive range of the sensor is 0.2–20 N, the second model can measure pressures by increments of approximately 1.9 g. As the adequate range of strength for brushing is between 150 and 200 g [26], we consider that the system should be able to measure by increments of 1.0 g. Although AIO-163202F-PE required a desktop PC, the previous model had difficulty in portability. We were required to bring the system to nursing schools or nursing homes to conduct experiments; therefore, we compromised the resolution.

The actual effects of the LED guides on learners must be examined experimentally. Our future research will include this.

3.2.2. Signal Selection by Multiplexers

This model has 14 teeth in the maxillary and mandibular jaws each, and every tooth has two sides to be brushed: the labial and lingual sides. As a result, 56 pressure sensors are required to apply the method described in Section 3.1. We used 14 analog multiplexers (CD74HC4067: Texas Instruments Inc.) to switch the target sensors to be recorded. Each multiplexer connects four sensors. The combination of four sensors was decided as follows: we divided all 56 sensors into four groups (groups 0 to 3) based on their location (labial side maxillary jaw, labial side mandibular jaw, lingual side maxillary jaw, lingual side mandibular jaw). Subsequently, we offset the number of sensors in each group (from 0 to 13, from left to right when viewed from a user) (**Fig. 6**). From this numbering, four sensors with the same offset number are connected to the same multiplexer (they all have different group numbers from 0 to 3). The microcomputer emits the same switching signal to all the multiplexers to select one of the four groups. After the group (from 0 to 3) is chosen incrementally, the microcomputer selects the offset (from 0 to 13) incrementally by a designated time interval. By the end period of recoding at offset 13, the microcomputer selects the next group. The offset number begins from 0 again. If the offset reaches 13 in group 3, the recording procedure is complete at the time.

The sampling rate is 5.31 samples per second. According to the sampling theorem, it is sufficient to sample the double maximum frequency to reconstruct the original wave. Considering that the actual target patients of oral care are elderly people, we assume that there are at most 2.5 round trips of a brush per second in brushing practice.

4. Visualization

4.1. Software for Visualization

All the signals from the pressure sensors are stored in the memory of the microcomputer. At the end of a recording, stored signals are transmitted to the software on a PC

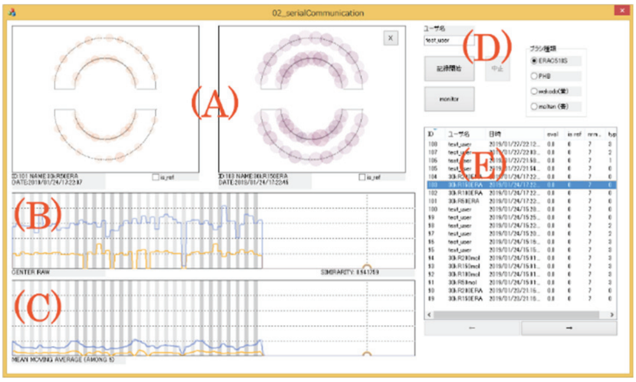

Fig. 7. GUI of the software.

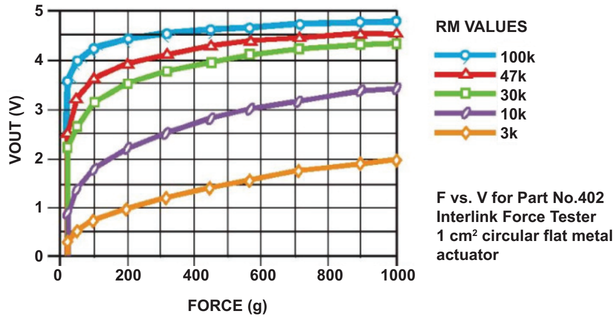

Fig. 8. Force vs. V_{out} curves of FSR pressure sensor varying registers [f].

via serial communication for visualization. The software has a function to store records in the database. We implemented the software using Visual C++ programming language with Microsoft Foundation Class, which is an application framework for Windows.

The software processes the recording data as follows: (1) parse the string obtained by serial communication, (2) convert the resulting A/D-converted discrete signals to corresponding weights in grams according to the location of the sensor where the signal comes from, and (3) visualize the result by plots on the graphical user interface (GUI).

Figure 7 shows the GUI of the software. The GUI is composed of: (A) two dentition model diagrams, (B) time series, (C) moving averaged time series, (D) operation buttons, and (E) a data manager. The questionnaire survey we conducted [8] indicated that the visualization software requires functions that compare two different records. Thus, we implemented two dentition model diagrams in (A) and time series (B) and (C). They can display two different records in different colors simultaneously. The visualized signals for teeth diagrams (A) and time series (B) are from sets of one target tooth and do not include signals from the neighboring teeth of the target. In contrast, moving averaged time series (C) visualizes the moving average of the past 5-time steps using signals from the target tooth and those from four neighboring teeth of the target. The moving averaged value (in grams) for a target tooth at time step t v_t in the time series (C) is calculated using the following equation in the general scenario.

$$v_t = \frac{1}{I} \sum_{i=-\lfloor \frac{I}{2} \rfloor}^{\lfloor \frac{I}{2} \rfloor} \frac{1}{J} \sum_{j=-\lfloor \frac{J}{2} \rfloor}^{\lfloor \frac{J}{2} \rfloor} v_{ij}, \quad \dots\dots\dots \quad (1)$$

where i is the index of time, j is the index of location centered on a target tooth, $\lfloor \cdot \rfloor$ is the floor function, and v_{ij} represents the value corresponding to the j-th tooth from a target tooth at the i-th time step. We used $I = 5$ and $J = 5$.

4.2. Recording Without Navigation

We conducted several trials for caregivers to use the developed simulator. We obtained opinions that state that the duration of the recording was too short and the LED guides transitioned too quickly. We modified the software to change the duration of recording by 10 preset lengths between 52 and 147 s. Before modification, the available duration was only 52 s.

We also developed a function to record the user's oral care practice without any navigation. This function can be applied to record practices by oral care experts. These records are expected to include some features of the experts' behavior. If the feature is available, some practical models for oral care can be extracted. Our future research will include this direction.

4.3. Calibration

The signals from the pressure sensors cannot directly indicate the force. General oral care textbooks request caregivers to apply a specific load to each care target tooth. Therefore, the software must display the load using a brush as a force. Therefore, we conducted sensor calibration for the system. The procedure was as follows: (1) apply weights of 0, 50, 100, 150, and 200 g to the brush using a piece of equipment to measure brushing force (Brushing Mate: The LION Foundation for Dental Health) [e], (2) record A/D-converted signals with a resolution of 10 bits by applying the weights for all sensors in the model; and (3) plot a weights-signal strength graph for each sensor and obtain the equations for the approximated curve using Google Spreadsheets.

From **Fig. 8** [f], we assumed that the relationship between the force and output signal voltage can be approximated by the equation below:

$$y_n = a_n x_n^{b_n}, \quad \dots\dots\dots \quad (2)$$

where y_n is the strength of the signal of a sensor measured by volts, a_n and b_n are the coefficients calculated by approximation, x_n is the weight applied to the brush, and n is the index of the sensors, which ranges from 0 to 55. We can obtain the following formula from Eq. (2).

$$x_n = \sqrt[b_n]{\frac{y_n}{a_n}}. \quad \dots\dots\dots \quad (3)$$

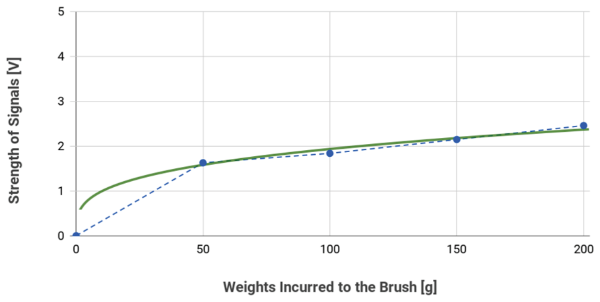

Fig. 9. Plot of weights vs. signal strength and approximated curve by power series.

We can estimate the weights applied to the brush at the n-th sensor using Eq. (3). **Fig. 9** shows a plot of the weights-signal strength plot and its approximation by power series. The dashed line shows a curve by the observed values, and the solid line shows the approximation curve.

We calculated approximations for all sensors with four types of brushes: standard toothbrush, soft toothbrush, and two types of sponge brushes. A user can select one of these on the software. The software reads the precalculated coefficients of a_n and b_n from the database and visualizes the estimated weights using Eq. (3).

5. Experiments

The calibration process is included in the weight estimation method of our system. Thus, we consider that it is beneficial for future researchers to indicate the effect of the calibration process instead of only indicating the results of the calibrated system. To indicate the difference of weight estimation between with and without calibration, we conducted experiments as follows: (1) create test data that consists of signals for 56 sensors by applying 100 g to each tooth (**Fig. 10**), (2) calculate two series of 56 estimated weights, which are "without calibration" and "with calibration," using Eq. (3) from the test data, and (3) test the difference of the average between the two series using the Student's t-test for paired samples. We used coefficients obtained by the calibration, and a set of constant coefficients without calibration for step (2). To calculate the set of coefficients without calibration, we used a single pressure sensor that was not embedded in the system. We attached the root of a tooth with hemispheres to the head of a sponge brush and directly pushed the surface of the sensor. This was conducted to avoid the coefficients being dependent on the specific location and structure of the tooth while creating a scenario similar to that in the system. We used Arduino Uno R3 to measure signals for the calculation of the coefficients without calibration. For the test data, we measured the signals three times and used their average for calculation. We used A/D-converted values for calculation, although **Figs. 9** and **10**, and equations we described used volts as the unit for easy understanding.

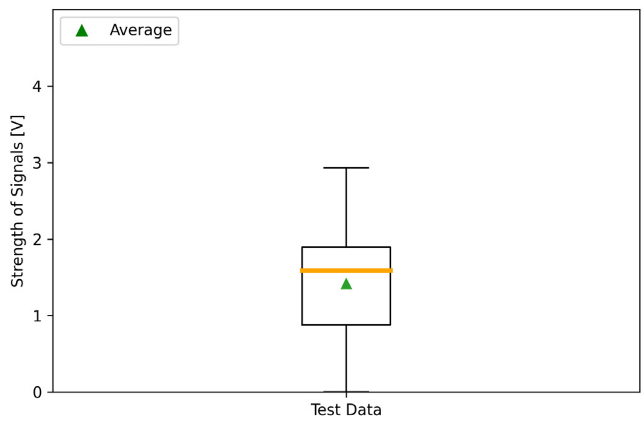

Fig. 10. Boxplot of the test data used in the experiment.

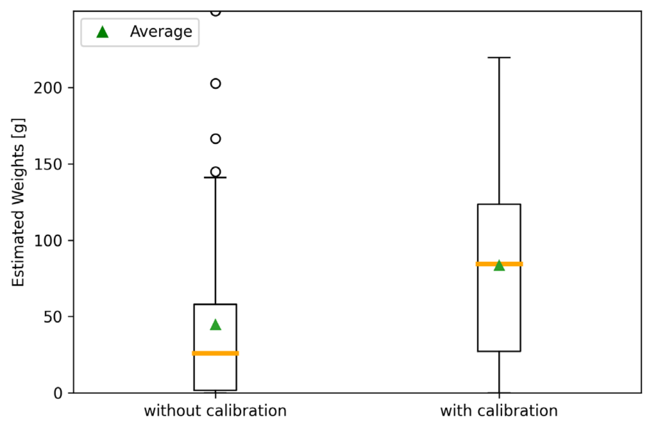

Fig. 11. Comparison of variation for estimated weights w/o and w/ calibration.

6. Results

The average estimated weights were 83.5 g (SD 56.3) with calibration and 44.7 g (SD 61.9) without calibration. The difference between these two averages was statistically significant ($p < .01$). Therefore, the calibration was meaningful to indicate a better estimation of the weights from the signals. **Fig. 11** shows a boxplot comparing the variation in the estimated weights with and without calibration for 56 sensors.

Large differences were still observed between the estimated weights and the actual loads. A possible cause is the structure of the teeth. Teeth on this device measure moments centering on the shaft holes (**Fig. 4**). Moments vary depending on the points of effort, even if the strength of the forces is the same. In addition, the friction between each tooth is not small. Resolving these problems is necessary to estimate accurate weights. We will address these concerns in future research.

7. Conclusion

We developed a second prototype of an oral care simulator that enables the training and reviewing of oral care procedures. We calibrated the developed system and observed that the procedure was effective in indicating a better estimation of weights that were applied to the teeth than in the scenario with no calibration. The gaps between the actual and estimated weights are large; thus, the system requires further improvements to measure loads accurately. Future research will also include evaluations of the proposed system by nurses or caregivers.

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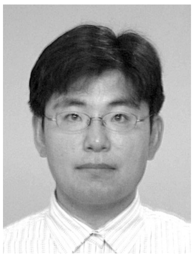

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