Bi-manual Haptic-based Periodontal Simulation with Finger Support and Vibrotactile Feedback

SAID CHEHABEDDINE, MUHAMMAD HASSAN JAMIL, and WANJOO PARK, New York University Abu Dhabi, United Arab Emirates
DIANNE L. SEFO, Clinical Associate Professor, Interim Chair, NYU College of Dentistry, USA
PETER M. LOOMER, Dean and Professor, School of Dentistry, University of Texas Health Science Center, USA
MOHAMAD EID, New York University Abu Dhabi, United Arab Emirates

The rise of virtual reality and haptic technologies has created exciting new applications in medical training and education. In a dental simulation, haptic technology can create the illusion of substances (teeth, gingiva, bone, etc.) by providing interaction forces within a simulated virtual world of the mouth. In this article, a haptic periodontal training simulation system, named Haptodont, is developed and evaluated for simulating periodontal probing. Thirty-two faculty members from New York University College of Dentistry were recruited and divided into three groups to evaluate three fundamental functionalities: Group 1 evaluated bi-manual 3 Degrees of Freedome (DoF) haptic interaction, Group 2 evaluated bi-manual 3 DoF haptic interaction with a finger support mechanism, and Group 3 evaluated bi-manual 3 DoF haptic interaction with finger support mechanism and vibrotactile feedback. The probe and mirror interactions were simulated with the Geomagic Touch haptic device whereas the finger support was implemented using the Novint Falcon device. The three groups conducted two probing tasks: healthy gingiva scenario with no pockets (2- to 3-mm depth) and periodontitis scenario with deep pockets (4- to 8-mm depth). Results demonstrated that experts performed comparably to clinical settings in terms of probing depth error (within 0.3 to 0.6 mm) and probing forces (less than 0.5 N). Furthermore, the finger support mechanism significantly improved the probing accuracy for periodontitis condition in the lingual region. The argument that probing the lingual region is more difficult than the buccal region is supported by quantitative evidence (significantly higher probing depth error and probing force). Further research is planned to improve the usability of the finger support, integrate the Haptodont system into the pre-clinical curriculum, and evaluate the Haptodont system with dental students as a learning tool.

CCS Concepts: • **Human-centered computing** → *Haptic devices*; • **Computing methodologies** → **Computer graphics**; **Virtual reality**; • **Computer systems organization** → *Robotics*; • **Networks** → Application layer protocols;

Additional Key Words and Phrases: Periodontal training, dental simulation, vibrotactile feedback

This research is funded by the New York University Abu Dhabi Research Enhancement Fund (RE217).

Authors' addresses: S. Chehabeddine, M. H. Jamil, W. Park, and M. Eid, New York University Abu Dhabi, P.O. Box 129188, Saadiyat Island, Abu Dhabi, United Arab Emirates; emails: {sc7388, hassan.jamil, wanjoo, mohamad.eid}@nyu.edu; D. L. Sefo, Clinical Associate Professor, Interim Chair, NYU College of Dentistry, 345 E. 24th Street, Room 622S, New York, USA; email: dlp6@nyu.edu; P. M. Loomer, Dean and Professor, School of Dentistry, University of Texas Health Science Center, Room 312W Dental Center, 421 First Avenue, San Antonio, Texas, USA; email: loomer@uthscsa.edu.

1551-6857/2021/04-ART28 $15.00
https://doi.org/10.1145/3421765

ACM Reference format:
Said Chehabeddine, Muhammad hassan Jamil, Wanjoo Park, Dianne L. Sefo, Peter M. Loomer, and Mohamad Eid. 2021. Bi-manual Haptic-based Periodontal Simulation with Finger Support and Vibrotactile Feedback. *ACM Trans. Multimedia Comput. Commun. Appl.* 17, 1, Article 28 (April 2021), 17 pages.
https://doi.org/10.1145/3421765

1 INTRODUCTION

Periodontal disease continually forms a sticky, colorless "plaque" around teeth caused by bacteria, which may in turn cause gingival inflammation of the periodontium [40]. When plaque calcifies, it becomes what is known as calculus. Calculus is a contributing factor for periodontal disease due to bacteria embedded into its porous surface. The periodontium consists of gingival tissue (also known as gums), cementum (outer layer of the root of a tooth), alveolar bone (the bone that surrounds teeth), and periodontal ligaments (tissue that connects cementum to the alveolar bone) [30]. There is a space between the gingiva and tooth surface called the gingival sulcus. When the disease is present in the periodontium, this space is called a periodontal pocket. Diagnosing periodontal disease involves probing to measure from the margin of the gingiva to the bottom of the space by using a periodontal probe. Periodontal procedures are typically taught through a sequence of instructor demonstrations, followed by the use of a practice manikin called a typodont, and finally via interaction with patients. Diagnosing and treating periodontal disease is perceived to be a challenging task [24], as it relies on the clinician's ability to recognize pockets, measure their depth, locate calculus, and remove calculus entirely based on the tactile sensation of the dental tools on the surfaces of dental tissues (as shown in Figure 1).

1.1 Periodontal Probing

A periodontal probe is a dental instrument that is used to measure gingival sulci depths to determine the health of the periodontium [35]. Periodontal probes have circumferential markings for readability and accuracy of periodontal probing procedures. To maintain accuracy, the probe must be used properly with great skill. The tip of the probe is placed with a light weight of 10–20 grams into the area of potential space between the tooth and the surrounding tissues (gingival sulcus). It is important to insert the probe into the sulcus with the correct orientation (angulation and adaptation) to reach down to the bottom of the sulcus. The probe should follow the contours of the root of the tooth for easy access to the bottom of the sulcus. While reaching down to the bottom of the sulcus, a part of the probe is obscured by the gingival tissue. The first circumferential marking visible above the gingiva is the measurement of the sulcular depth. A healthy gingival sulcus has an average depth of 2–3 mm with no bleeding upon probing. Depths greater than 3 mm are associated with gingival enlargement related to infection and/or detachment of the tooth from the surrounding bone, which is the indication of periodontitis. Deeper depths of the gingival sulcus as a result of gingival enlargement, but no loss of surrounding bone, is categorized as a gingival pocket. When bone loss is present, it is categorized as a periodontal pocket. The probe is then slowly moved around all six regions (Figure 4(b)) of the tooth to measure the different pocket depths. A common technique taught in dental programs is using finger rests (placed normally one to four teeth distant from the tooth), known as fulcrum, to stabilize the instrument while probing. The purpose of this technique is to improve the precision of the work, to prevent sudden movements, and to reduce the muscle stress of the operator. Rotation is needed to angle the probe around the anatomy of the tooth when walking the probe around the circumference of the tooth, while maintaining the probe tip on the base of the gingival sulcus or pocket. During this time, the anatomy of the tooth can be felt by the probe on one side of the probe and the gingival tissue can be felt on the other side.

Fig. 1. Probing technique with correct probe orientation and grip pose (with permission from the College of Dentistry of New York University).

1.2 Virtual Reality and Haptics in Dental Simulation

The variation among dental practitioners creates a challenge when it comes to educating dental students in the skills of periodontal practices [24]. Virtual reality (VR) can improve the training of periodontal procedures by standardizing the learning process and providing a safe yet highly customizable learning environment [32]. VR allows students to see a variety of simulated gingival/teeth health scenarios; the system can repeat the scenarios that the student had difficulties with, support and reinforce the learning of proper ergonomics and procedures, and provide students with standardized feedback in real time [16, 19, 26, 27, 32].

Given how periodontal education involves a high level of proficiency in manual dexterity, haptic technologies significantly enhance periodontal simulation training [25]. Haptic cues provide information beyond audio-visual cues (i.e., depth and material physical properties such as stiffness, surface texture, temperature, etc.), allowing trainees to feel and touch dental tissues. Kinesthetic haptic feedback in periodontal training is known in the literature [18, 36, 39]; however, a finger rest simulation with vibrotactile feedback has not yet been explored for periodontal training.

In our previous work [21], we proposed a system, named Haptodont, based on virtual reality and haptic technologies, to simulate periodontal procedures. In this article, the system was evaluated with a large group of dental educators for its ability to simulate periodontal probing procedures for three fundamental functionalities: bi-manual 3 Degrees of Freedom (DoF) force feedback, finger support mechanism, and vibrotactile feedback. To the best of our knowledge, the effectiveness of finger support and vibrotactile stimulation has never been examined for periodontal training. The remainder of the article is organized as follows. Section 2 analyzes the related work for haptic simulation in dental training. Section 3 presents the experimental method to evaluate the three functionalities of the Haptodont system. In Section 4, the performance of the three groups is presented and compared. Section 5 presents general discussion related to the subjective feedback about the finger rest and vibrotactile feedback. Finally, Section 6 summarizes the findings and provides directions for future work.

2 RELATED WORK

Dental simulators have been developed in academia and in industry. The concept design of a virtual reality dental training (VRDT) system was introduced in the late 1990s to practice cavity preparation [31]. Thomas et al. developed a training system that enables an operator to practice the detection of carious lesions [38]. More powerful dental simulation tools have since been developed including the VRDT system [5] and the Iowa Dental Surgical Simulator [20]. Several companies have been focusing on developing commercial VR dental training systems. Simodont [1] was developed by MOOG, Inc., and can simulate drilling and mirror reflection [20]. The Forsslund Dental system was developed to practice dental drilling and wisdom teeth extraction [14].

Researchers have also explored haptic technologies for periodontal simulation. The PerioSim system was developed to simulate three operations: pocket probing, calculus detection, and calculus removal [22]. Wang et al. developed a dental simulator with haptic feedback (iDental) and presented a user evaluation that included qualitative and quantitative analysis [39]. Results suggested that it is sufficient to use 3 DoF haptic rendering for single-point contact simulation but necessary to use 6 DoF (including torque feedback) haptic rendering for multi-region contact simulation. Previous studies have also shown that finger support reduces muscle stress and fatigue [12]. Therefore, it is one of the objectives of this study to evaluate a finger support mechanism functionality with the Haptodont system.

Research indicates that the use of vibrotactile feedback aids in acquiring and learning new motor skills in general [8, 23]. An example of tactile technology enhancing training procedures is the simulation of pulse palpation for the femoral artery in an interventional radiology procedure [9]. Three tactile technologies, piezoelectric pads, micro speakers, and a commercial pin array device from Aesthesis (Salford, United Kingdom), were compared on the basis of their suitability to be attached to a trainee's fingertips or a force feedback device's end effector [34]. Another example of tactile technology enhancing training is a small portable tactile device, consisting of a three-by-two array of pneumatic balloons, that has been developed by Culjat et al. [10]. The device adds tactile cues to the controllers of the da Vinci surgical system from Intuitive Surgical Inc. (Sunnyvale, CA). Results demonstrated that the tactile information provided by the device is suitable for training purposes. Recently, vibrotactile simulation is also shown to be beneficial for teaching caries detection to dental students [23] where dental educators rated tactile feedback as a highly valuable source of information for detecting caries.

In our previous work [21], we developed the Haptodont system to enhance the realism of periodontal training simulation by examining a custom grip to attach the dental instrument to the haptic devices. The system also included two haptic devices to simulate the dental instrument and a mirror interaction to provide bi-manual interaction, with a finger rest mechanism based on parallel manipulation. Furthermore, the system utilized immersive VR visual display to dramatically improve visualization and interaction in dental training.

The objective of the present study is to examine the effectiveness of three functionalities of the Haptodont system, namely the bi-manual 3 DoF force feedback, the finger support mechanism, and the vibrotactile cues. Due to complexity, cost, and fidelity challenges associated with rendering torque feedback, we examine the effectiveness of vibrotactile feedback to substitute torque feedback along with bi-manual 3 DoF haptic interaction. To the best of our knowledge, none of the previous work examined the effectiveness of vibrotactile feedback for periodontal training simulation.

The following hypotheses are examined in this study:

(1) expert's probing performance with the Haptodont system is comparable to standard expert's performance with real patients,
(2) a finger support mechanism significantly improves expert's performance while probing deep pockets, and
(3) vibrotactile feedback improves the quality of experience during a probing task.

3 HAPTODONT SYSTEM DESCRIPTION

The Haptodont system, as shown in Figure 2, consists of a wooden frame, 2 three-dimensional (3D) Systems Geomagic Touch haptic devices simulating the probe and mirror interactions, custom

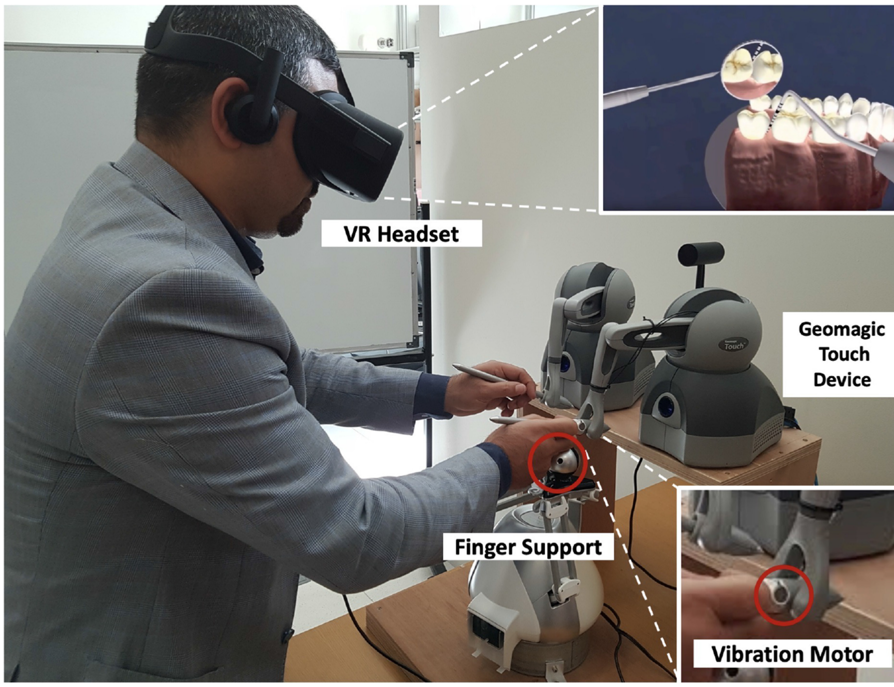
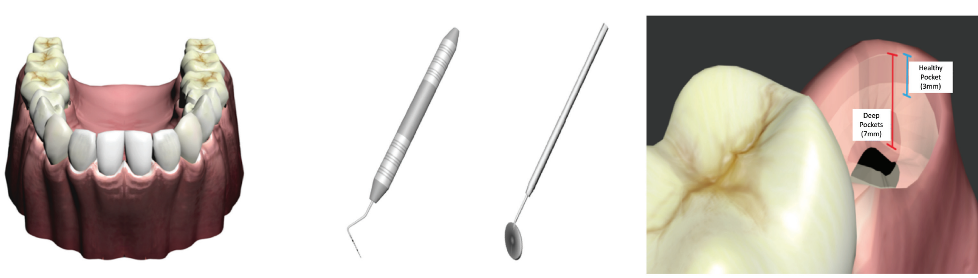


Fig. 2. Haptodont system setup.



(a) Teeth and gingiva models (b) Dental instruments models (c) Pocket Modeling

Fig. 3. Typodont model, probe and mirror models, and pocket modeling example.

grips made from real dental instruments to enhance the tactile experience of grasping the tools, a Novint Falcon device to provide finger support, a vibration motor (Vibrating Mini Motor Disc from Adafruit Industries LLC) fitted to a 3D printed socket on the dominant-hand Geomagic Touch device, and a VR headset (Oculus Rift) to provide an immersive visual experience.

3.1 3D Modeling

To simulate the periodontal probing task and realistic pocket depths, a mandibular, lower jaw, typodont model was created using Autodesk 3ds Max software. The typodont model included teeth and gingiva surfaces of the oral cavity as shown in Figure 3(a).

The virtual probing instrument is modeled based on the University of North Carolina UNC–12 probe, which can be seen in Figure 3(b). The model was designed using Autodesk 3ds Max software to perform probing tasks in the virtual environment. The UNC-12 probe has circumferential markings from 1 to 12 mm at each mm with color blocks between the 4- to 5-mm markings and the 9- to 10-mm markings.

A dental mirror was designed to provide indirect vision inside the simulation environment to facilitate the reading of correct probe measurements. Indirect vision is required while probing as well as other dental procedures where direct visibility is difficult or impossible. The lingual side of the anterior maxillary teeth is a notable area where mouth mirrors are often used while performing periodontal procedures. Figure 3(b) shows the mouth mirror designed in 3d software to provide indirect vision.

3.2 Haptic and Visual Rendering

For the force feedback rendering of the Haptodont system, haptic models for the probe and mirror objects were created using Chai3D to simulate single point of haptic interaction with both tools [33]. Chai3D is an open source, cross-platform C++ framework for haptic rendering, visualization, and interactive real-time simulation. Chai3D supports many commercially available haptic devices and provides an easily-programmable interface to the haptic devices (including the Geomagic Touch and Novint Falcon devices). No torque feedback is rendered, since the haptic interfaces utilized in this study are incapable of rendering torque. In an effort to compensate for the lack of torque feedback, vibrotactile cues are rendered based on a set of vibration logical points that are distributed in diamond shape pattern to detect collision between the rotating tool and the surrounding objects (tooth and/or gingiva), as elaborated in detail later in Figure 6.

A finger-proxy model was used to render the 3D mesh object where a virtual proxy is represented as a substitute for the physical finger in the simulation environment [33]. The proxy object always moved toward the goal position. The proxy motion was made to locally minimize the distance between the proxy and the device position. Haptic interaction forces were computed by modelling a virtual spring between the proxy and the haptic device position. The total force was calculated using Equation (1),

$$F = -k \times \Delta x + F_s + F_d + F_p, \tag{1}$$

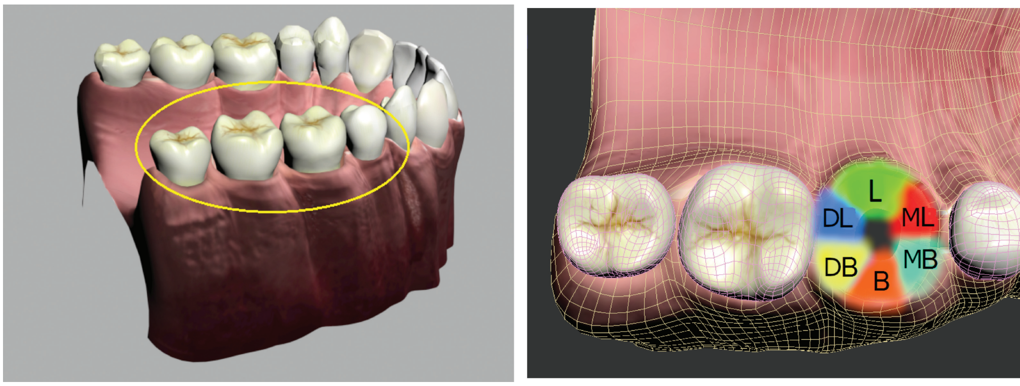
where k is the stiffness of the model, Δx is the distance between proxy and physical device position, F_s and F_d are the static and dynamic frictional forces applied, and F_p is the force calculated through the finger proxy algorithm [33]. The stiffness property of the spring can be adjusted in the Chai3D framework. Note that the physical properties of the simulated models, namely the stiffness and surface friction were measured using a data-driven modeling approach for both the teeth and the gingiva [6].

As for visual rendering, the Haptodont system was complemented by the Oculus VR head mounted display for an immersive visual experience. The Oculus VR headset provides a wide 110° field of view with 1,080 × 1,200 pixel resolution per eye at a refresh rate of 90 Hz. Chai3D provides support for the synchronized visual and haptic rendering in virtual space thus enhancing the realism of visual experience.

3.3 Pocket Design

Figure 4(a) demonstrates the typodont model with pockets located at the right mandibular molars (first, second, and third molars) and at the second premolar. Six probing sites around each tooth are recorded, namely the mesial lingual (ML), lingual (L), distal lingual (DL), mesial buccal (MB), buccal (B), and distal buccal (DB), as shown in Figure 4(b).

To create a pocket in a probing site, the Haptodont system deforms the site away from the teeth, simulating a detached gingiva. The degree of detachment is controlled by the configured pocket depth, which is mapped to the probing sites through a texture map based on Figure 4(b). This results



(a) Mandibular with highlighted teeth with pockets

(b) Different tooth regions containing pockets (ML, L, DL, MB, B and DB correspond to mesial lingual, lingual, distal lingual, mesial buccal, buccal and distal regions respectively)

Fig. 4. The active teeth and dental regions with periodontal pockets.

ALGORITHM 1: Pocket smoothing algorithm.

Data: Neighboring pockets formed by vertex sets V_1 & V_2. Choose V_2 as the shallower pocket.
$T \leftarrow$ Vertices in $V_1 \cup V_2$ that form the transition.
zT $\leftarrow$ zMax(T) – zMin(T)
for *each vertex* $\boldsymbol{v} \in T$ **do**
  vzNormalized $\leftarrow$ (**v** .z – zMax(T))/zT
  if $\boldsymbol{v} \in V_2$ **then**
    $\alpha \leftarrow (2/\pi)\arccos(2\text{vzNormalized} - 1) - 1$
    w $\leftarrow$ **v** 's neighbor in $V_2 \setminus T$ farthest from T
    direction $\leftarrow$ **w** – **v**
    v $\leftarrow$ **v** $-\alpha \cdot$ **direction** ▷ Shifts **v** away from the transition
  else
    Repeat for V_1 with α's sign flipped

in a vertical, discrete, and unnatural transition of pocket depth between probing sites. Hence, each transition is smoothed into a slidelike, continuous, natural form, as outlined in Algorithm 1.

To simulate the periodontitis condition, two scenarios were developed based off realistic settings; one with healthy pocket depths (2- to 3-mm depth) and one with periodontitis condition (4- to 8-mm depth). Table 1 highlights the two different scenarios created for the periodontal probing simulation in this study.

3.4 Haptodont Functionalities

The Haptodont system is designed to support a large set of functionalities that can be implemented for particular training setups. Examples of such functionalities include bi-manual 3 DoF force feedback simulation, realistic graphic/haptic modeling of human tissue, 3D immersive visual feedback using VR display, finger support mechanism, torque feedback, vibrotactile feedback, multi-modal recording and playback, performance evaluation, and so on. A group of dental educators from the College of Dentistry of New York University was consulted to identify the top three functionalities to improve learning outcomes of dental students. These functionalities were identified as: (1) bi-manual 3 DoF force feedback interaction, (2) finger support mechanism, and (3) vibrotactile

Table 1. Healthy and Periodontitis Scenarios for Pocket Depths along Different Teeth Sites

(a) Healthy Pocket Scenario (Pocket Depth (PD) 2–3 mm)

ToothNumber	32B			31B			30B			29B		
Site	MB	B	DB	MB	B	DB	MB	B	DB	MB	B	DB
PD	3	2	3	3	2	3	3	3	3	3	2	3
PD	3	2	3	3	3	3	3	2	3	3	2	3
Site	ML	L	DL	ML	L	DL	ML	L	DL	ML	L	DL
ToothNumber	32L			31L			30L			29L		

(b) Periodontitis Condition (Pocket Depth (PD): 4–8 mm)

ToothNumber	32B			31B			30B			29B		
Site	MB	B	DB	MB	B	DB	MB	B	DB	MB	B	DB
PD	7	4	7	5	5	5	6	3	6	8	4	8
PD	7	4	7	5	2	5	6	6	6	8	4	8
Site	ML	L	DL	ML	L	DL	ML	L	DL	ML	L	DL
ToothNumber	32L			31L			30L			29L		

feedback to highlight significant events in the simulation. However, considering the complexity and cost of developing torque feedback hardware, it was decided to evaluate whether vibrotactile feedback may somehow compensate for the torque feedback. A key factor of the success of this system is to maintain an economic solution that most dental schools can afford.

3.4.1 Configuration-1: Bi-Manual 3 DoF Haptic Interaction. Configuration 1 comprised two Geomagic Touch devices rendering bi-manual, 3 DoF translation force feedback to simulate dental probe and dental mirror interactions. Oculus Rift is utilized to provide participants with immersive visual experience. Neither finger support nor vibrotactile feedback is provided in this functionality.

3.4.2 Configuration-2: Bi-Manual 3 DoF Haptic Interaction with Finger Support. Probing periodontal pockets requires the clinician to use a specific technique to better control the force that they are exerting as well as to help reduce fatigue. Correct technique while performing periodontal pocket probing requires that the clinicians rest their fulcrum finger, which is the ring finger being used as a lever, on one to four teeth distant from the tooth that is being probed [3]. To accomplish this within the virtual simulation, a Novint Falcon device was used as seen in Figure 2, a supporting location is set to move depending on the tooth that is being probed into discrete preset locations based on a calibration performed by two dental experts. An overview of finger support control algorithm is shown in Algorithm 2. The algorithm retrieves the probe position and transforms it to the finger support workspace. The transformed position is adjusted using the height (Δ_1) and lateral (Δ_2) offset values to accommodate specific hand size and orientation (offset values are calculated through a separate calibration process for a particular user). Finally, the finger support device moves its end effector to the designated position and renders maximum stiffness to provide the highest resistance possible against movement. A close look at the finger support mechanism is shown in Figure 5.

3.4.3 Configuration-3: Bi-Manual 3 DoF Haptic Interaction with Finger Support and Vibrotactile Feedback. Torque feedback is not available for the Geomagic Touch device; only translation forces exerted at the tip of the probe can be rendered. Consequently, vibrotactile feedback is utilized to provide users with cues about the rotation of the probe, primarily if the probe is rotated into teeth or gingiva. The vibrotactile feedback is rendered using two types of vibration cues; a strong cue

Fig. 5. Finger support system.

ALGORITHM 2: Finger support control algorithm

Data: Adjust finger support position **P** in workspace based on finger proxy position, height offset Δ_1 and lateral offset Δ_2

initialize

while *true* **do**

  update proxy position

  if *support connected* **then**

    C ← **fingerProxyGlobalPosition**

    if C *over tooth$_n$* **then**

      S ← **supportProxyPosition**

      $P_{x,y} \leftarrow S_{z,y}$ ▷ Transform Coordinates

      $P_z \leftarrow S_x + \Delta_1$

      ϕ ← **proxyRotation**

      if $\phi_x < 120°$ **then**

        $P_y \leftarrow P_y + \Delta_2$

      else

        $P_y \leftarrow P_y - \Delta_2$

      moveSupportTo(**P**)

      setMaxDeviceStiffness

(a Pulse-Width Modulation (PWM) at a 100% duty cycle or 5 V) for a probe overly rotated into a tooth, and a weak vibration cue (a PWM at a 67% duty cycle or 3.3 V) for a probe overly rotated into a gingiva, with the active area being the measurement length of the probe. A probe handle colliding or experiencing an unrealistic occlusion does not render a vibration. The rationale behind these vibrotactile cues is that gingiva is a soft object and teeth are hard, so a strong cue was used on the teeth to highlight the difference in stiffness.

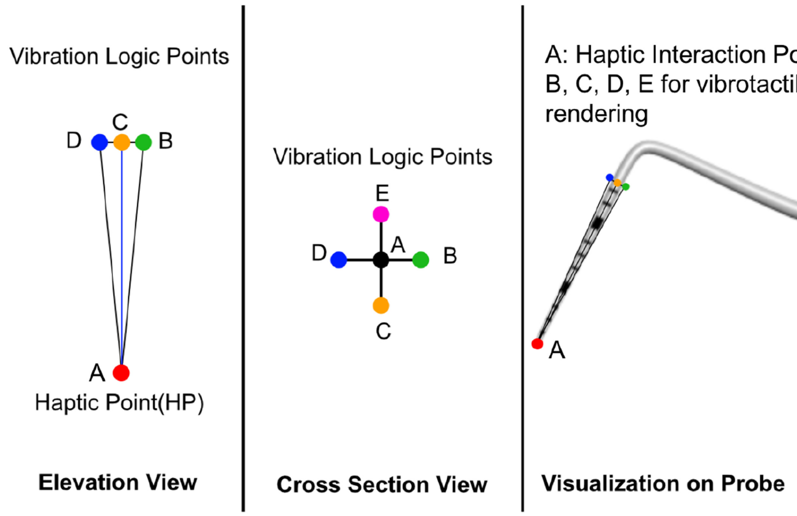


Fig. 6. Haptic point and vibration logic point diagram.

The vibrotactile feedback rendering was designed with a focus on an ability to create clear and distinctive vibration cues to provide tactile information in the absence of torque feedback. One primary issue with haptic devices that have torque feedback capability is the limitation of the number of haptic points available. Currently torque feedback capable machines such as the Phantom premium device use two haptic points to calculate such torque [2]; however, this setup does not render realistic forces in this use case. The forces being experienced while probing a periodontal pocket are the result of interactions along the entirety of the probe. Thus the number of points required to render feedback effectively is significantly higher than two, which results in a significant increase in the computational complexity; decreasing the fidelity of the experience. Vibrotactile feedback was explored as an alternative to provide information when users had their dental probing tool angled in such a way as to cause an unrealistic occlusion into an impenetrable object, such as a tooth or gingiva, as a stand-in to the forces that would be experienced along the probe.

The Vibrating Mini Motor Disc from Adafruit Industries LLC was fitted into a 3D printed socket that can be seen in Figure 2. The motor's light weight of 0.91 g and its low starting voltage of 2.0 V allowed for the ability to use it within the simulation and create distinctive vibration cues through the use of PWM, while maintaining a realistic weight for the haptic stylus as compared to a dental probing tool [4].

To render vibrotactile cues, a set of Vibration Logic Points (VLPs) is implemented where the points are distributed in a diamond shape pattern as seen in Figure 6. The Haptic Point (HP) is at the tip of the probe and the VLPs are just above the 12-mm marking on the probe. VLP A is at the center of the probe shaft with each of the other VLPs on the surface of the probe shaft. If an occlusion caused by the gingiva occurs on any line, then a soft vibration cue will occur; however, an occlusion caused by a tooth will only render a cue if it occurs on line HP-A, where the cue is a distinctively stronger vibration.

To implement the distinctive cues necessary, the Arduino Uno microcontroller was utilized to control the vibration motor depending on the type of unallowable occlusion. The microcontroller constantly receives a code from the main program via the serial port, this code then informs the type of vibration the microcontroller must execute. For a probe over angled into a tooth, the microcontroller would send a consistent logical high signal of 5 V, thus producing a strong vibration; while for a probe over angled into the gingiva a PWM at a 67% duty cycle at 490 Hz was used to produce a distinctively softer vibration. The voltages were set via the microcontroller through a motor breakout, for more consistent and safer operation.

4 EXPERIMENTAL DESIGN

4.1 Participants

The participants consisted of 32 faculty members from the College of Dentistry of New York University, all were experts in periodontal instrumentation. On average, participants had 7.66 ± 3.05 years of teaching experience and 8.59 ± 2.82 years of clinical training experience. Participants were divided into three groups: (1) the Control group (C) with 12 participants to evaluate configuration 1 with bi-manual 3 DoF force interaction, (2) the Finger Support group (FS) with 10 participants to evaluate bi-manual 3 DoF force interaction with finger support, and (3) Finger Support and Vibrotactile feedback Group (FSV) with 10 participants to evaluate bi-manual 3 DoF interaction with finger support and vibrotactile feedback. It is worth noting that the three groups were balanced in terms of their teaching and clinical experiences and familiarity with VR and haptic technologies (no statistical differences were found across the three groups).

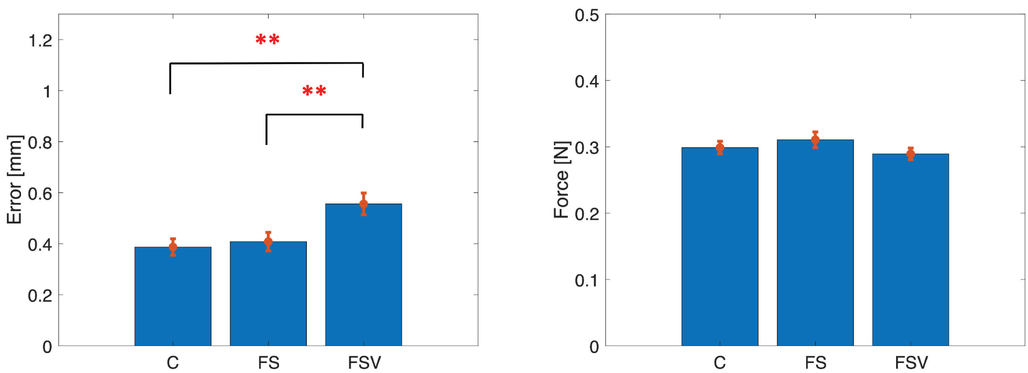
The background of the participants was evaluated through questionnaire, asking the number of years of teaching and clinical experience, whether their teaching experience was in the pre-clinics, clinics, or both. They were also asked to rate their comfort level with the use of technology (4-point Likert scale ranging from very comfortable to not at all) and how often they have used VR or haptic technologies prior to the experiment (4-point Likert scale ranging from often to never). Participants were uniformly distributed among the three groups to ensure balanced groups based on background; which was verified through collective analysis where there were no statistical differences based on background experience between the groups.

4.2 Experimental Protocol

The experimental protocols for the three functionalities were identical. Prior to the probing exercise, participants completed a pre-experiment questionnaire that inquired about various background factors such as clinical experience, teaching experience, VR experience, among others. After completing the pre-test questionnaire, participants went through an acclimation period of experiencing the setup to become acquainted with the Haptodont system, understanding of the haptic feedback, and for the test groups to familiarize themselves with the added functionalities assigned to them. Participants were then given a short break of 2 minutes before beginning the two haptic tasks.

Each participant completed the two probing tasks, namely the healthy and severe probing tasks. One round of probing task was performed to avoid any learning effects. The probing tasks consisted of the participants calling out pocket depth measurements (in mm) of the teeth with active pocket depths on both buccal and lingual sides. These measurements were recorded in a periodontal chart by the experiment moderator. Between the tasks, participants were given a short break of no longer than 2 minutes to help reduce eye fatigue and nausea. The first task involved probing a healthy gingiva, whereas the second task examined a periodontitis condition, the specific pocket depth configurations can be seen in Table 1. After completing the second task, participants filled out the post-experiment questionnaire to provide their feedback about the system.

To evaluate the participant's performance, the probing accuracy on buccal, lingual, and overall is measured. The probing error is calculated as the difference between the actual pocket depth and the depth reported by the participants (1 mm means the error is within ±1 mm from the correct



(a) Mean and standard error for the probing depth error.

(b) Mean and standard error for the probing force.

Fig. 7. Performance for healthy and periodontitis conditions combined. C, FS, and FSV indicate control, fingure support, and fingure support + vibrotactile feedback groups. Kruskal–Wallis test, Bonferroni correction, **$p < 0.01$.

pocket depth [15]). Furthermore, the exerted force during probing is also measured and included in the performance analysis. Note that the task completing time, i.e., the time it takes to complete the probing task, is not considered for evaluating the probing performance, since it is not a common metric for evaluating probing performance [35].

A post-experiment questionnaire was implemented to capture expert's experience on realism, usefulness, and suggestions for improvement. A 5-point Likert scale is used for the survey questions. Statistical analysis is conducted to compare the performance across the three groups. Since the data were not normally distributed (Jarque-Bera normality test), non-parametric methods were utilized. Kruskal–Wallis test was considered to investigate differences in probing depth error and probing force data for the three groups where multiple comparison issue was corrected by Bonferroni correction.

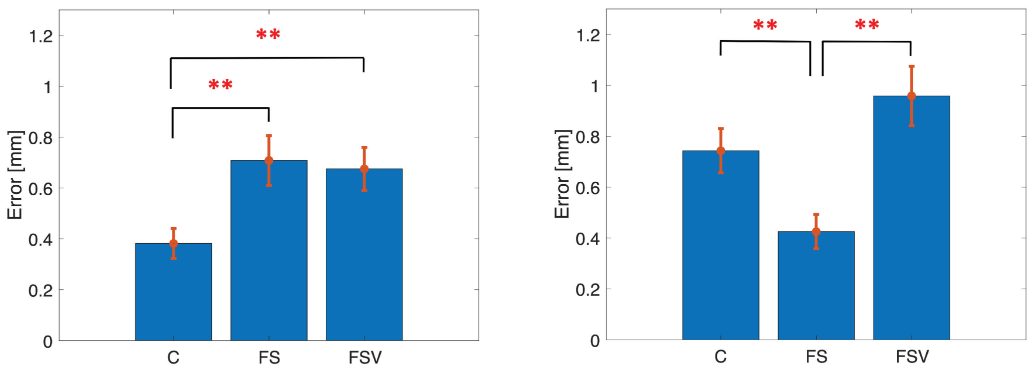
5 RESULTS

This section reports on performance evaluation for the three configurations, both quantitatively using average probing depth error and average probing force and qualitatively by analyzing the post-experiment questionnaire responses.

5.1 Quantitative Evaluation

The mean and standard error for the probing depth error for the three groups is shown in Figure 7(a). The three groups produced a probing depth error between 0.3 and 0.6 mm. Previous research has shown that the average error for manual probing ranges between 0.3 and 0.6 mm [13, 15, 28]. However, the mean and standard error for the probing forces for the three groups is shown in Figure 7(b). The average probing force is found to be less than 0.5 N for the three groups. Previous research has shown that the average probing force in clinical settings is less than 0.5 N [17]. Results from probing depth error and probing forces demonstrate that the three configurations have produced satisfactory performance as compared to clinical performance. Therefore, hypothesis 1 is accepted.

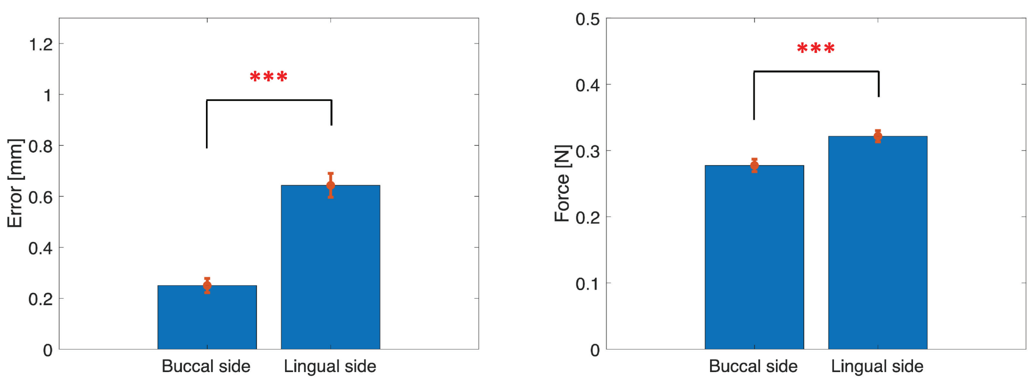
Comparing the performance across the three groups, results showed significant differences in performance between healthy and periodontitis conditions. As shown in Figure 8(a), the probing depth error for the C group was statistically smaller than that of the FS or the FSV groups for



(a) Lingual side in healthy model

(b) Lingual side in periodontitis model

Fig. 8. Probing depth error for the three groups (C, FS, and FSV indicate control, fingure support, and fingure support + vibrotactile feedback, respectively). Kruskal–Wallis test, Bonferroni correction, ** $p < 0.01$.



(a) Error of Depth between Buccal and Lingual sides

(b) Force difference between Buccal and Lingual sides

Fig. 9. Differences in depth error and force between buccal and lingual sides. Wilcoxon rank-sum test, *** $p < 0.001$.

the healthy condition, lingual region (Kruskal–Wallis test, Bonferroni correction, $p < 0.01$). However, in the case of periodontitis condition where deep pockets exist, the probing depth error for the FS group was statistically smaller than the other two groups (Figure 8(b), Kruskal–Wallis test, Bonferroni correction, $p < 0.01$) for the lingual region. This demonstrates that as the complexity of probing increases (periodontitis condition, lingual region), the finger support mechanism plays a significant role in improving probing accuracy [29], which implies that hypothesis 2 is accepted.

It is known in periodontal education that probing the lingual region is more challenging than the buccal region [7]. We examined this phenomenon by comparing probing performance between the lingual and buccal regions. Figure 9(a) shows that the probing error is significantly smaller on the buccal region than the lingual region (Wilcoxon rank-sum test, $p < 0.001$). However, Figure 9(b) shows that participants applied significantly larger forces for the lingual region compared to the buccal region (Wilcoxon rank-sum test, $p < 0.001$). These results serve as a quantitative evidence that the lingual region is generally more difficult to probe than the buccal region.

5.2 Subjective Evaluation

The questionnaire prompted participants about their speciality, teaching experience (number of years, pre-clinical/clinical or both), and whether they are familiar with VR and haptic technologies. They were asked to rate the usefulness of the simulation as a learning tool, to rate the system against traditional typodonts in terms of tactile and visual realism, usability, learning effectiveness, acceptance, and difficulty. Finally, experts are provided with open-ended questions to identify features that must improve as well as suggest novel features.

The faculty response on usefulness as a learning tool and realism of tactile sensation as well as the visual realism of probe, mirror, teeth, and gingiva in comparison to probing traditional typodont models is examined, since dental and dental hygiene students usually practice on typodont before mock clinical practice [37].

As for the question of usefulness as a learning tool, the participants rated 3.72 ± 0.52 with ratings: 5, extremely; 4 very; 3, moderately; 2, slightly; 1, not at all. That is significantly higher score than 1, Wilcoxon signed-rank test, $p < 0.01$. As for the visual realism of teeth and gingiva, the participants of FS and FSV groups rated higher score than the participants of C group. This might be as a result of complemented finger support and vibrotactile feedback provided in the simulation in case of FS and FSV group compared to C. This is in line with previous findings that realistic haptic feedback enhances audiovisual experience [11].

From the collection of suggestions made by the faculty participants to improve the Haptodont, there is a clear need to rotate the teeth model in the virtual environment. There were also recommendations for the addition of a face, cheeks, and tongue. These are anatomical structures that can provide additional tactile feedback when touched by the virtual tools, especially when retraction is needed. The addition of calculus, bleeding, suppuration, teeth crowding, missing teeth, and blanching of gingival tissue to the touch were also suggested to create a more realistic oral environment.

Results showed that 75% of participants (24 of 32) rated the tactile realism to be better or the same as that of the typodont. There was no significant differences across the three groups, therefore, hypothesis 3 is rejected as there is no statistical evidence that vibrotactile feedback improved the expert's quality of experience. These subjective evaluation demonstrate that the 3D models for the typodont and the dental instruments are satisfactorily realistic to experts in dental training.

To gain feedback from the faculty participants to guide further development of the Haptodont simulator, the participants were asked the following questions in the post-experiment questionnaire: (1) What features need to be improved in the Haptodont system? (2) What features do you suggest be added to the Haptodont system? As for question (1), the most common suggestion was to improve the finger support mechanism as it seems to go off-track of the participant's hand occasionally. To provide a reliable finger support, a more accurate hands tracking system must be implemented. As for question (2), the responses varied from adding a feature to rotate the model to better access the lingual surfaces, to add head/cheeks/tongue models to create a more realistic context for the simulation, to track the human hand and show it in the virtual environment.

5.3 Discussion

The faculty participants completed the probing tasks with comparable performance to clinical settings, in the three configurations (average probing depth error between 0.3 mm and 0.6 mm and average probing force less than 0.5 N). It is also shown that the finger support mechanism significantly reduced the probing depth error during a probing task with deep pockets in the lingual region. Furthermore, the lingual regions were significantly more difficult to probe (worse probing depth error and higher probing forces were statistically significant). The decrease in accuracy on the lingual surfaces may be caused by various reasons. Comments from participants suggest difficulty in visual clarity when working on the lingual. This may be due to the reflection on the mirror for indirect vision not being clear enough or the inability to rotate the model to see the area more directly. All participants are experts to prove pocket depth. Thus, in the case of the buccal side or the pockets with no pockets (2- to 3-mm depth), it could be very easy for them. As shown in 6(a), we did not see a significant difference between C and FS groups, and infer that unnecessary vibration would increase the error.

The current study demonstrated the effectiveness and desire for the finger rest for improved performance in periodontitis condition and to reduce fatigue based on several comments made by C group. The finger support mechanism significantly reduced the probing depth error when deep pockets were probed in the lingual region. The need to improve the existing finger rest mechanism was clear as commented by the FS and FSV groups. The placement of the current finger rest was programmed to the chosen locations by the two clinicians in the experimental team. One clinician is a trained dental hygienist with relatively small hands, and the other a trained periodontist with large hands. The dental hygienist places her fulcrum finger toward the front end of the finger rest and the periodontist places his finger toward the back end. The initial thought was that it would cover a range of clinician hand sizes. However, this experiment demonstrated other factors to consider, the variation in grasp and location a clinician chooses to hold the instrument handle and placement of the fulcrum finger relative to the tooth being probed. Although there is a standard method of how to hold the handle and where to place the fulcrum finger, there is a deviation to this standard that some clinicians may develop when out in clinical practice. While it is reasonable to make the necessary changes to the current finger support simulation to accommodate for these variations, it should also be considered that leaving it in the current state could support disciplined fulcrum.

The vibrotactile feedback was found to be helpful by all participants in FSV group, which were given this feature. However, while probing a healthy gingiva, it seems that the vibrotactile cues was distracting, since the probing depth errors were significantly higher than the other two groups (Figure 7(a)). Furthermore, vibrotactile feedback seems to worsen the performance for more difficult probing tasks (lingual periodontitis condition) (Figure 8(b)). These findings provide further support to reject hypothesis 3.

There are some limitations to this study. All faculty participants were from the same institution and only from two different departments within the college. However, these are the departments that provide the preclinical training of periodontal probing to all students at this institution. Not all faculty participants teach in the preclinical setting, which may have hindered these participants' ability to evaluate the system relative to a traditional typodont model currently being used in preclinical training. The current study aimed to evaluate Haptodont functionalities for simulating periodontal probing exercise and not as a learning tool. Nevertheless, for a majority of the faculty participants (over 97%), the Haptodont system is considered a useful learning tool for preclinical periodontal instrumentation training that has the potential to improve learning effectiveness compared to the traditional typodont model. This study does not address whether finger support mechanism and vibrotactile feedback are useful for learning. In the future work, longitudinal study with dental students is needed to investigate learning outcomes and training effects.

6 CONCLUSIONS

The current study investigated the effectiveness of three functionalities of the Haptodont simulation system: (1) bi-manual 3 DoF force feedback, (2) bi-manual 3 DoF force feedback with finger support, and (3) bi-manual 3 DoF force feedback with finger support and vibrotactile feedback. Results demonstrated that experts performed comparably to clinical settings in terms of probing error (between 0.3 and 0.6 mm) and probing forces (less than 0.5 N). Furthermore, finger support mechanism significantly improve the probing accuracy for periodontitis condition in the lingual region. The argument that probing the lingual region is more difficult than the buccal region is supported by quantitative evidence.

The data and evaluations by the faculty will be used to guide further development of the Haptodont system to enhance its applicability in dental education. Our future work involves adding the following features to the existing simulation (in this particular order): anatomy of the mouth/head to provide realistic context to the simulation, system (haptic and visual) guidance for demonstrating correct probing technique, a graphical user interface to record and evaluate the learner's performance, enhance real-time feedback to the learner, and a graphical user interface to customize the probing exercise. Furthermore, we would like to investigate which of these functionalities are the most effective as a learning tool for dental students learning periodontal probing. Based on the expert's feedback, we plan to improve the ergonomics of the finger support, since several participants highlighted that it was not always calibrated properly to their hands. Another interesting future direction would be to utilize the Haptodont system to benchmark periodontal probing methods.

REFERENCES

[1] [n.d.]. MOOG Simodont system. Retrieved from http://www.moog.com/markets /medical-dental-simulation/haptic-technology-in-simodont.

[2] CHAI3D Online Documentation. 2019. Chapter 17: Haptic rendering. Retrieved from https://www.chai3d.org/download/doc/html/chapter17-haptics.html.

[3] The American Board of Dental Examiners. 2019. Patient treatment clinical examination manual. Retrieved from https://www.cdcaexams.org/documents/manuals/Dental_Hygiene_PTCE2019.pdf.

[4] Online Data Sheet. 2019. Precision microdrives. Retrieved from https://www.precisionmicrodrives.com/wp-content/uploads/2016/04/310-101-datasheet.pdf.

[5] Virtual reality dental training system. Retrieved from polhemus.com/blog/entry/virtual-reality-in-dental-training-and-simulation.

[6] Arsen Abdulali, Ruslan Rakhmatov, Tatyana Ogay, and Seokhee Jeon. 2018. Data-driven modeling and rendering of force responses from elastic tool deformation. *Sensors* 18, 1 (2018), 237.

[7] Dick Steven Barendregt et al. 2009. *Probing Around Teeth.* Ph.D. Dissertation. Universiteit van Amsterdam [Host].

[8] E. Van Breda, S. Verwulgen, W. Saeys, K. Wuyts, T. Peeters, and S. Truijen. 2017. Vibrotactile feedback as a tool to improve motor learning and sports performance: A systematic review. *BMJ Open Sport Exercise Med.* 3, 1 (2017).

[9] T. Coles, N. W. John, D. A. Gould, and D. G. Caldwell. 2009. Haptic palpation for the femoral pulse in virtual interventional radiology. In *Proceedings of the 2nd International Conference on Advances in Computer-Human Interactions (ACHI'09)*, 193–198.

[10] M. Culjat, C. H. King, M. Franco, J. Bisley, W. Grundfest, and E. Dutson. 2008. Pneumatic balloon actuators for tactile feedback in robotic surgery. *Industr. Robot: An Intl. J.* 35, 5 (2008), 449–455.

[11] Fabien Danieau, Anatole Lécuyer, Philippe Guillotel, Julien Fleureau, Nicolas Mollet, and Marc Christie. 2012. Enhancing audiovisual experience with haptic feedback: A survey on HAV. *IEEE Trans. Hapt.* 6, 2 (2012), 193–205.

[12] H. Dong, A. Barr, P. Loomer, and D. Rempel. 2005. The effects of finger rest positions on hand muscle load and pinch force in simulated dental hygiene work. *J. Dent. Educ.* 69, 4 (2005), 453–460.

[13] Joseph L. Fleiss, Jonathan Mann, Myunghee Paik, Joseph Goultchin, and Neal W. Chilton. 1991. A study of inter and intraexaminer reliability of pocket depth and attachment level. *J. Periodont. Res.* 26, 2 (1991), 122–128.

[14] J. Forsslund, El Sallnas, and K. J. Palmerius. 2009. A user-centered designed FOSS implementation of bone surgery simulations. *IEEE World Hapt.* (2009), 391–392.

[15] Arthur F. Hefti. 1997. Periodontal probing. *Crit. Rev. Oral Biol. Med.* 8, 3 (1997), 336–356.

[16] W. Hollis, L. A. Darnell, and T. L. Hottel. 2011. Computer assisted learning: A new paradigm in dental education. *J. Tenn. Dent. Assoc.* 91 (2011), 8–14.

[17] Birte Holtfreter, Dietrich Alte, Christian Schwahn, Moïse Desvarieux, and Thomas Kocher. 2012. Effects of different manual periodontal probes on periodontal measurements. *J. Clin. Periodontol.* 39, 11 (2012), 1032–1041.

[18] J. C. Huegel and M. K. O'Malley. 2010. Progressive haptic and visual guidance for training in a virtual dynamic task. In *Proceedings of the IEEE Haptics Symposium*, 343–50.

[19] B. S. Issenberg, W. C. Mcgaghie, E. R. Petrusa, D. L. Gordon, and R. J. Scalese. 2005. Features and uses of high-fidelity medical simulations that lead to effective learning: A BEME systematic review. *Med. Teach.* 27, 1 (2005), 10–28.

[20] L. Johnson, G. Thomas, S. Dow, and C. Stanford. 2001. An initial evaluation of the Iowa dental surgical simulator. *J. Dent. Educ.* 64, 12 (2001), 847–53.

[21] G. Karafotias, G. Korres, D. Sefo, P. Loomer, and M. Eid. 2017. Towards a realistic haptic-based dental simulation. In *Proceedings of the 2017 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE'17)*, 1–6.

[22] M. Kolesnikov, M. Zefran, A. D. Steinberg, and P. G. Bashook. 2009. PerioSim: Haptic virtual reality simulator for sensorimotor skill acquisition in dentistry. In *Proceedings of the 2009 IEEE International Conference on Robotics and Automation*, 689–694.

[23] K. J. Kuchenbecker, R. C. Parajon, and M. P. Maggio. 2017. Evaluation of a vibrotactile simulator for dental caries detection. *Simul Healthcare* 12, 3 (2017), 148–156.

[24] S. K. Lanning, S. D. Pelok, B. C. Williams, P. S. Richards, D. P. Sarment, T. J. Oh, and L. K. McCauley. 2005. Variation in periodontal diagnosis and treatment planning among clinical instructors. *J. Dent. Educ.* 69, 3 (2005), 325–337.

[25] C. Luciano, P. Banerjee, and T. DeFanti. 2009. Haptics-based virtual reality periodontal training simulator. *Virt. Real.* 13, 2 (2009), 69–85.

[26] W. C. McGaghie, S. B. Issenberg, E. R. Petrusa, and R. J. Scalese. 2010. A critical review of simulation based medical education research: 2003-2009. *Med. Educ.* 44 (2010), 50–63.

[27] I. Motola, L. A. Devine, H. S. Chung, J. E. Sullivan, and S. B. Issenberg. 2013. Simulation in healthcare education: A best evidence practical guide. *AMEE Guide No. 82. Med. Teach.* 35, 10 (2013), e15110–30.

[28] Joy B. Osbom, Jill L. Stoltenberg, Beverly A. Huso, Dorothee M. Aeppli, and Bruce L. Pihlstrom. 1992. Comparison of measurement variability in subjects with moderate periodontitis using a conventional and constant force periodontal probe. *J. Periodontol.* 63, 4 (1992), 283–289.

[29] Philip M. Preshaw. 2015. Detection and diagnosis of periodontal conditions amenable to prevention. In *BMC Oral Health*, Vol. 15. Springer, S5.

[30] NIH Publication. 2013. Periodontal (gum) disease: Causes, symptoms, and treatments. *NIH Publ.* 46, 13-1142 (2013).

[31] J. F. Ranta and W. A. Aviles. 1999. The virtual reality dental training system-simulating dental procedures for the purpose of training dental students using haptics. In *Proceedings of the 4th PHANTOM Users Group Workshop* (1999).

[32] E. Roy, M. M. Bakr, and R. George. 2017. The need for virtual reality simulators in dental education: A review. *Saud. Dent. J.* 29, 2 (2017), 41–47.

[33] D. C. Ruspini, K. Kolarov, and O. Khatib. 1997. The haptic display of complex graphical environments. In *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques.* 345–352.

[34] Ioannis Sarakoglou, M. Bezdicek, N. Tsagarakis, and Darwin G. Caldwell. 2006. Free to touch: A portable tactile display for 3d surface texture exploration. In *Proceedings of the IEEE RSJ International Conference on Intelligent Robots and Systems.* IEEE, 3587–3592.

[35] K. N. Al Shayeb, W. Turner, and D. G. Gillam. 2014. Periodontal probing: A review. *Prim. Dent. J.* 3, 3 (2014), 25–9.

[36] R. Sigrist, G. Rauter, R. Riener, and P. Wolf. 2013. Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychon. Bull. Rev.* 20 (2013), 21–53.

[37] M. Sunaga, M. Minabe, K. Inagaki, and A. Kinoshita. 2016. Effectiveness of a specially designed dental model for training, evaluation, and standardization of pocket probing. *J. Dent. Educ.* 80, 12 (2016), 1430–1439.

[38] G. Thomas, L. Johnson, S. Dow, and C. Stanford. 2000. The design and testing of a force feedback dental simulator. *Comput. Methods Progr. Biomed.* 64, 1 (2000), 53–64.

[39] D. Wang, Y. Zhang, J. Hou, Y. Wang, P. Lv, Y. Chen, and H. Zhao. 2012. iDental: A haptic-based dental simulator and its preliminary user evaluation. *IEEE Trans. Hapt.* 5, 4 (2012), 332–343.

[40] Mea Weinberg, Cheryl Westphal, Stuart Froum, Milton Palat, and Robert Schoor. 2014. *Comprehensive Periodontics for the Dental Hygienist.* Pearson Higher Ed.

Received February 2020; revised August 2020; accepted August 2020