# Towards a Realistic Haptic-based Dental Simulation

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***Abstract*** *– Recently there has been a remarkable increase in the use of technology in medical and dental education. Haptics technologies allow the operator to interact with the simulation environment using the sense of touch. In this paper we investigate three facets for realistic simulation with periodontists: (1) a custom grip is designed to attach dental instruments to the haptic interface in order to enhance the grip, (2) two haptic interfaces are utilized to simulate haptic feedback with both the dental instrument and the mirror instrument, and (3) a finger rest mechanism based on parallel manipulation is used for the intraoral fulcrum during probing. A haptic-based simulation system, named the Haptodont, is developed to evaluate the three facets of realism. A subjective evaluation is conducted with five dental experts to collect more information about perceptions, insights, and experiences to shape the second generation requirements and design for the Haptodont system. Future work will focus on further development and quantitative usability testing (with both dental experts and students) with the goal to improve the educational experience, outcomes and skills of clinicians/students.*

***Keywords*** *– Haptic interfaces, Force feedback, Medical simulation, Human computer interaction*

## I. INTRODUCTION

Over the last decade there has been a remarkable increase in the use of information technology in both learning and training of medical procedures using computer simulators [1][2]. For dental procedures, the use of a simulator has been proved to increase patient safety and reduce risk associated with human errors by allowing dental students to develop skills more efficiently in a shorter period of time [3][4][5].

In particular, acquiring abilities and skills to perform periodontal procedures takes more than observing patients, diagnosing and managing the disease, but also needs a practical experience of the tactile sensation. Traditionally, dental and dental hygiene students gain such expertise in the laboratory through two stages: first, students train on artificial teeth placed within a manikin head, using real dental instruments, and second, students perform periodontal procedures on real patients under the close supervision of their instructors [6]. Existing simulation tools do not provide dental students with the same usability experience compared to performing on live patients [7]. Therefore, a system that is closer to reality, both haptically and graphically, will improve learning outcomes and the overall quality of experience.

Haptics refers to the science of sensing and manipulation through touch [8][9][10]. Haptic-based simulators employ a haptic interface where the learner holds a pen-like stylus (whose virtual representation is shown on the screen) instead of the real dental instrument and tactile sensations are reproduced in the hand of the operator [11][12][13]. In this paper, we developed and evaluated three functions that enhance the realism of periodontal simulation. Using virtual reality and haptics technologies, the Haptodont system provides learners with a more realistic experience to replicate real-world diagnosis and/or treatment procedures of periodontal diseases. The learner uses dental instruments attached to the haptic interfaces via custom grips, interacts with the 3D virtual models of teeth, gingiva, bone, calculus, instruments, etc., and feels their physical tactile properties with both hands. The learner is also provided a finger rest mechanism for the intraoral fulcrum during instrumentation.

The remainder of the article is structured as follows. Section II describes the related work in dental simulators. The subsystems and the components of the Haptodont system are analyzed in Section III. Section IV first presents the experts that participated in our evaluation study and then reports their feedback. Lastly, our conclusions and future endeavors are summarized in Section V.

## II. RELATED WORK

Dental simulators have been developed both in the academia and the industry. The concept design of a Virtual Reality Dental Training (VRDT) system was introduced in the late nineties to practice cavity preparation [14]. Thomas et al. developed a training system that enables an operator to practice the detection of carious lesions [15]. In recent years, more powerful dental simulation tools have been developed including the Virtual Reality Dental Training System (VRDTS) [16], Iowa Dental Surgical Simulator (IDSS) [17], and 3DDental (no longer available) [18]. Several companies have been focusing on developing commercial dental training systems. The Simodont was developed by MOOG, Inc., and can simulate drilling and mirror reflection [19]. The Forsslind Dental system was developed to practice dental drilling and wisdom teeth extraction [20]. Another interesting study was the comparison of virtual reality and augmented reality modalities in a haptic dental training simulator [21].

Periodontal procedures require clinicians to depend primarily on their tactile sensation, for both diagnostic and surgical procedures. This makes haptic technology ideally suited for periodontal simulators. The PerioSim simulator was developed to simulate three operations: pocket probing, calculus detection, and calculus removal [22]. Similarly, the hapTel of Tse et al. [23] was created to train students for caries removal and dental drilling. Wang et al. developed a haptics-based dental simulator (iDental) and presented a user evaluation that included qualitative and quantitative analysis [24]. Results suggested that it is necessary to use 6-DOF haptic rendering for multi-region contacts simulation.

978-1-5386-0979-8/17/$31.00

Furthermore, a more practical dental simulator must include simulation of deformable bodies such as tongue and gingival, and simulation of occlusion of tongue and cheek on teeth, etc.

Even though the work in [24] has proven to be a successful tool for faster acquisition of skills and has resulted in overall positive student perception, there remain few challenges. First of all, the user experience is somehow distorted since students use the haptic interface stylus rather than the real dental instruments. Second, two-hands simulation must be supported to recreate two-instruments interaction experience (for example the mirror instrument is commonly used for retraction). Finally, fulcrum is not applicable since there is no simulation of finger rest.

The Haptodont system focuses on creating more realistic interaction by: (1) developing a custom grip to allow several types of instruments, in different shapes and sizes to be attached to the haptic interface (the appropriate 3D models for these instruments are also shown in the virtual environment), (2) supporting two-hands interaction using two haptic interfaces (one haptic interface provides physical interaction between the dominant hand and the dental instrument, whereas the other haptic interface supports physical interaction between the non-dominant hand and the mirror instrument), and (3) building a finger rest device that follows the dominant hand haptic interface and provides physical support for the finger when fulcruming on teeth. We also present a pilot study to evaluate the three functionalities with five experts in periodontal instrumentation.

## III. SYSTEM ARCHITECTURE AND DESIGN

### *A. System Architecture*

The Haptodont system architecture is shown in Figure 1. The trainer configures the simulation environment by controlling the graphical/physical properties of the simulation via the Graphical User Interface (GUI). A predefined set of common configurations/tasks is created and stored as test cases for easy retrieval and setup. The Environment Simulation maintains the graphic and haptic models that comprise the dental training environment. Three database components are associated with the Environment Simulation module: the Quality of Performance (QoP) database that stores interactions between the learner and the simulation environment, the Haptic Models database contains the physical properties of objects populating the simulation environment (such as stiffness, surface texture, friction), and the Graphic Models database that manages the 3D graphic models for the simulated environment.

Audio/Visual interfaces provide auditory and visual interactions with the learner (such as speakers and microphones for auditory input/output and a screen for 2D visual display). The non-dominant hand haptic interface displays force feedback that are felt with the dental mirror, whereas the dominant hand haptic interface renders force interactions with the dental instrument (probe or explorer). A snapshot of the Haptodont system is shown in Figure 2.

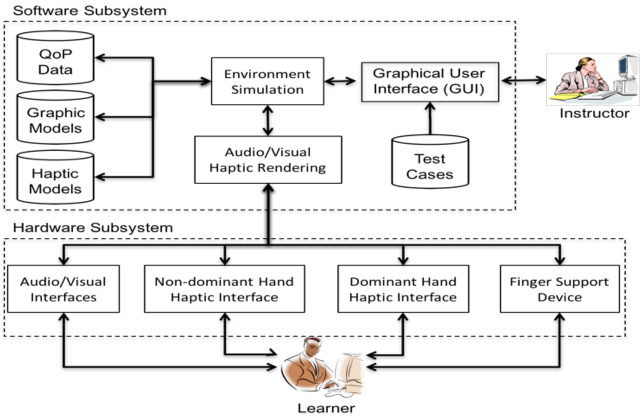


Fig. 1. Component diagram for the Haptodont system.

Fig. 2. Haptodont implementation.

### *B. Hardware Subsystem*

Figure 3 captures further details of the hardware subsystem. Three parallel streams of data are exchanged between the hardware and the software simulation subsystem. The dominant hand haptic interface captures movements and provides force feedback for the dental instrument (probe), whereas the non-dominant hand haptic interface captures movements and provides force feedback to the mirror instrument. The finger rest device acquires the dominant hand haptic interface position from the simulation software and moves its end effector underneath the dominant hand position (so when the learner wants to rest their finger, the end effector will be right beneath it).

*1) Custom Grip for Haptic Interfaces:* A distinguished feature of the Haptodont system is to provide a custom grip that connects the haptic interface to a real dental instrument. The Geomagic Touch end effector is replaced with a hollow custom handle. The instrument nib is cut and connected to the haptic interface through the custom grip. A demonstration of this process is shown in Figure 4. The objective here is to evaluate whether having the tactile experience of touching the real instruments is necessary for realistic simulation, and if so a custom grip will be designed to facilitate connecting various instruments to the haptic interface.

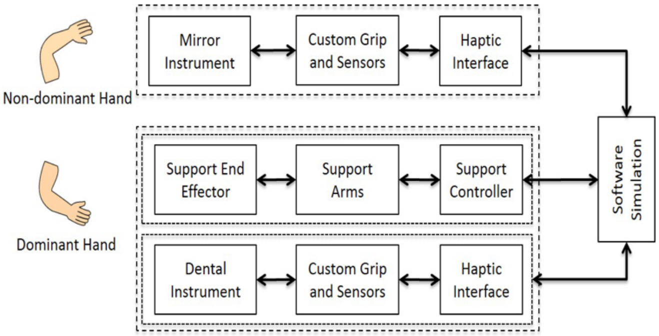


Fig. 3. A block diagram for the Haptodont system.

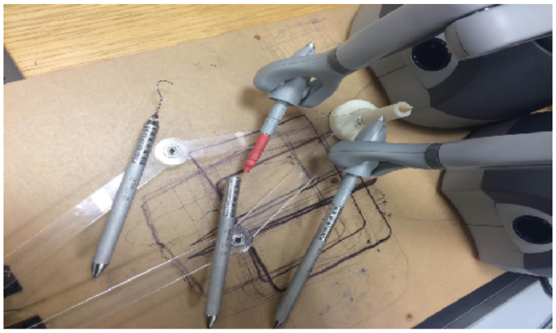


Fig. 4. Custom grip for the haptic interfaces.

*2) Finger Rest Device:* A two-degrees-of-freedom parallel robot is designed to provide finger rest and fulcrum for the learner as they perform periodontal procedures (a 3D model is shown in Figure 5(a)). The finger rest device uses two servo motors, each controlling the movement of one robotic arm, which are connected together through the end effector base. The finger rest device receives position data (x,y) from the dominant hand haptic interface, calculates the angles needed to move the end effector to that position, and instructs the servo motors to generate the required torques to make the actual movements. The inverse kinematics analysis for the parallel robot is shown in Figure 5 [27].

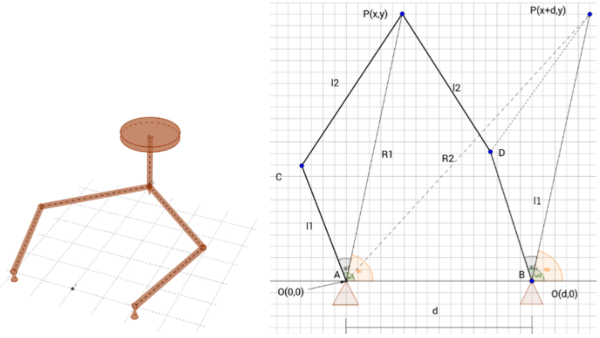


Fig. 5. (left) Finger rest 3D model, (right) The inverse kinematics problem.

The finger rest end effector is customizable in three ways, as shown in Figure 6: (1) the elevation of the finger rest compared to the haptic interaction workspace is manually adjustable, (2) a variable offset along the xy-plane enables adapting to different hand sizes, and (3) the end effector shape is also customizable (for instance connecting a real tooth, a flat rectangular/circular surface, or a gingiva-like surface).

Fig. 6. (left) 2 DoF parallel robotic device for finger rest, (right) Finger rest end effector with a tooth model attached.

### *C. Software Subsystem*

The software subsystem is implemented using CHAI3D framework [25]. CHAI3D is an open source set of C++ libraries for computer haptics, visualization, and interactive real-time simulation. One important reason for selecting CHAI3D for the software implementation is the support for multiple haptic interfaces within the same application.

*1) 3D Modeling:* Models for the objects that populate the simulation environment are utilized from a previous work. Figure 7 shows the 3D models for the mirror instrument, the periodontal probe, and the periodontal scaler. 3D models for the dental instruments, upper and lower teeth, gingiva, and tongue are shown in Figure 8(a). Finally, Figure 8(b) demonstrates a simple example of calculus modeling.

Fig. 7. Models for the mirror instrument (top), periodontal probe (middle), and periodontal scaler (bottom).

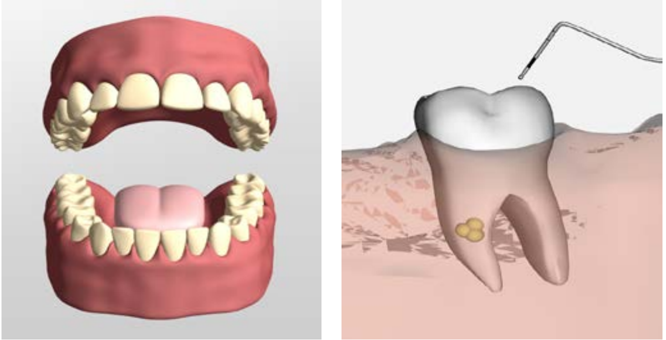


Fig. 8. (left) Models for the top and bottom gingiva and all the teeth, and (right) a simulation of calculus.

2) Configuration Software: The Haptodont system provides a graphical user interface that enables instructors to create customized training sessions for learners. As shown in Figure 9, the GUI has five groups of configurations: teeth configuration (existing/missing), gingiva configuration (color and inflammation properties), probing sections configuration (location and depth of pocket), calculus configuration (enable/disable, severity, location, etc.), and other properties (any future developments such as tooth mobility simulation).

3) Simulation Software: The implementation architecture for the simulation software is shown in Figure 10. The CHAI3D main function maintains the simulation environment by interacting with various other components for haptic, audio, and visual rendering. It also contains predefined functions that are utilized to create the scene's camera and lighting, and to load the various 3D meshes such as the teeth, gingiva, tongue, and tools (these models are stored in a separate repository as shown in Figure 10). Note that the arrow from the meshes to the CHAI3D main function is bidirectional because the gingiva model is loaded and then manipulated to create the various pockets. These models are also assigned haptic properties (stiffness, static and dynamic friction) so they can interact within the haptic rendering. The Finger Support Driver uses a serial port connection to update the position of the finger support end effector.

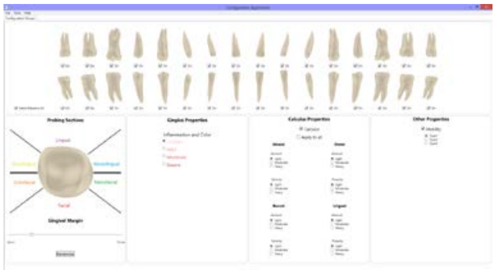


Fig. 9. Configuration GUI.

The CHAI3D main function manages the simulation scene using a node system (Figure 11), where the world node is the root node, and every child node is rendered in the scene using the OpenGL rendering API. Some meshes are also associated with audio buffers and audio sources in order to play specific sound effects (for instance when the probe tool is touching the teeth). The haptic rendering is implemented using the OpenHaptics API based on the virtual "finger-proxy" algorithm developed by Ruspini and colleagues [26].

## IV. EVALUATION STUDY

### A. Participating Experts

The pilot usability study is conducted with five experts in periodontal education (4 periodontists and 1 dental hygienist). One periodontist is currently a clinical professor and chair of periodontology at New York University College of Dentistry, with over 20 years of experience in the areas of periodontology, oral microbiology and occupational ergonomics. Another participant is a dental hygienist with 17 years of experience in periodontal instrumentation and 15 years of teaching experience with specific training and expertise in clinical education. Two periodontists have more than 20 years of experience operating in dental clinics. The fifth participant is a graduating student (who would provide some perspective from a student point of view).

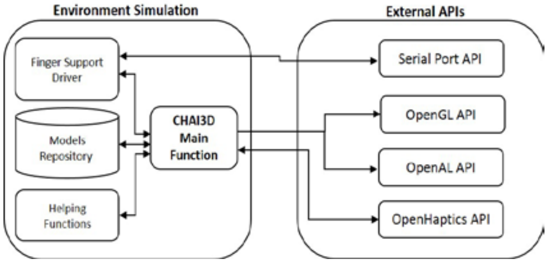


Fig. 10. Implementation architecture.

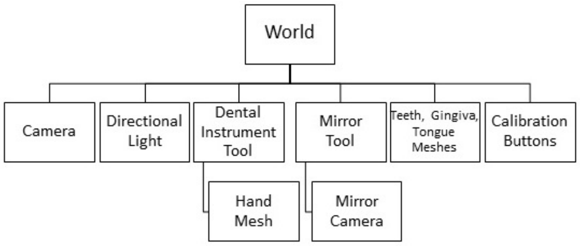


Fig. 11. Components of Environment Simulation.

### B. Experimental Setup and Test-bed

We designed a qualitative experimental study to evaluate the three different facets of realistic interactions. The evaluation was intended to be subjective so that we could collect as much information as possible in order to define the requirements for the second generation Haptodont system. Figure 12 shows one of the experts performing a probing task. The evaluation study consisted of two parts: evaluating the hardware and the software subsystem, following a series of features outlined for assessment. The participants were required to conduct a periodontal probing task to explore the pocket depth of two mandibular posterior teeth for measurement. The study was completed on a computer with the following specifications: Intel Xeon 2 CPUs at 2.30Ghz, 32Gb RAM, Quadro K5000 GPU, running on the Windows 8.1 64-bit operating system.

1) Haptic interface - custom handle, workspace, degrees of freedom: The feature to assess was the use of the real dental instrument handle instead of the haptic interface stylus. Initially, the experts explored the simulation environment by holding the haptic interface stylus and performed a probing task. Afterwards, the stylus is replaced by the dental instrument via the custom handle. The same task was performed holding the new handle. The exploration procedure was conducted with only one haptic

interface for the dominant hand. Moreover, we inquired if the Geomagic Touch workspace (160 W x 120 H x 70 D mm) and the permitted rotation (≈300°) are large enough to accommodate periodontal procedures simulation, and if a haptic interface with 6-DOF (force and torque) feedback is required.

Fig. 12. Experimental setup.

The experts agreed that using the real instrument handle for the grip was more realistic and comfortable. However, attaching the real instrument handle has increased the overall weight of the handle, so this must be compensated by the software. The workspace was large enough to work on every tooth in the human lower and upper jaw. The permitted rotation was restricting. The 300° rotation of the handle will need to be moved from its current location on the haptic interface to allow for 150 ° per direction of use. The 6-DOF force feedback was not required for the probing procedure but might be desired in the scaling procedure.

*2) Use of two haptic interfaces:* The second feature was whether using two haptic interfaces provides an added value to the user experience. The experts were asked to perform the same exploration as before twice: the first time using only one haptic interface and the second time using both interfaces.

The experts thought that the two haptic interfaces simulation served two purposes: (1) the primary haptic interface conveys tactile sensations to the dominant hand while performing periodontal procedures, (2) the secondary haptic interface is necessary to provide the function of indirect vision and retracting the cheeks and tongue. The experts reported an issue when working with two devices: the tips of the haptic interfaces were colliding when they were placing the tools very close to each other. To overcome this, one expert suggested holding the grips in the opposite direction and translate the haptic interaction points of the two interfaces.

*3) Finger rest device:* The objective of this test was to assess how closely the finger rest device followed the movement of the user's dominant hand. The geometry and texture of the finger rest end-effector were also investigated as well as the calibration of the device.

The experts felt that the robotic arm accurately follows the user's movements, but it must also follow the fulcrum finger (which is usually the ring finger) and not where the user holds the tool. At the time of testing, the rest device could reach any position in the workspace, which the experts thought was not necessary and that the movement should be limited to only follow the shape of the arch of the teeth and match the camera view for a more realistic experience. Finally, in order to provide rest for upper and lower jaws, the experts' recommendation was to implement a third motor to automatically adjust the height of the end effector or to change the shape/size of the end effector to provide realistic contact with the finger.

When calibrating the finger rest device, the experts felt that it was too complicated to calibrate the end effector in the position they wanted. One reason for this was the lack of depth perception. Future development will utilize immersive virtual reality display (such as Oculus Rift). Also, the translation step size should be smaller to have finer control of the calibration. They also proposed two new buttons: one to hide the calibration buttons after the calibration is completed and another to turn on and off the entire finger rest system.

*4) 3D models:* The quality of the 3D models is evaluated, namely teeth, gingiva, tongue, dental instruments, and dominant hand. Experts were asked if the details of the models, both graphically and haptically, were satisfactory. The experts suggested that the teeth should have higher stiffness and lower friction, the gingiva should have lower stiffness and lower friction (than what is currently used). The low friction in both cases is because of the saliva that exists in the oral area.

*5) Graphical user interface:* The experts performed a cognitive walkthrough to inspect the configuration GUI. It was concluded that the GUI should be simple, containing all the options and parameters in one tab. Moreover, preset test cases must be implemented (with drop down menus, for example, to load these test cases) to facilitate quick composition of learning tasks. The experts also suggested extra options, such as select/deselect-all buttons and/or other functionalities. The experts thought that more options for camera positioning are needed. In practice, the clinician has different points of view of the patient depending on which areas the instrumentation is happening (upper/lower and anterior/posterior teeth). It was also considered to utilize a voice recognition system to change the camera position that will mimic a clinician asking the patient to move their head.

*6) One-to-one correlation:* The one-to-one correspondence between the real and the virtual world is also examined with the experts. In other words, if the user moves the instrument grip 1 cm in the real world, then the corresponding virtual model will also move precisely 1 cm in the same direction. The experts thought that the one-to-one correlation system is realistic, since trainees should learn to perform in exact dimensions and not scaled ones.

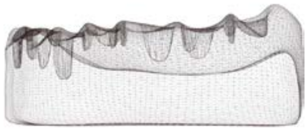
*7) Probing procedure:* Three probing tasks were created to simulate various pocket sizes/depths. All tasks involved manipulating the lower left quarter of the gingiva. The first configuration included a healthy gingiva without any pockets. The second configuration comprised pockets in the various sectors with 2 to 8 mm depth with abrupt cavities. The third configuration used the same pocket properties except that cavities were smoothed up and widened. Figure 13 demonstrates the difference between abrupt and smoothed pocket simulation. The experts found that the third configuration was the most realistic because the pocket contour should be smooth and gradually change its depth. Also, the pocket should be included in a whole sector, not just a portion of it as it happened in the second configuration. There would be a benefit of incorporating a voice recognition system for recording the user's probing depth measurements.

## V. CONCLUSION AND FUTURE WORK

In this paper, we present a study to evaluate three functions that aim to enhance the realism of haptic experience in periodontal simulation. Five experts in periodontal education evaluated the system. The two haptic interfaces are necessary to provide a realistic interaction. Experts also complimented the finger rest device and suggested that a more intuitive and easy calibration is needed. Finally, a cognitive walkthrough with the GUI was conducted to identify usability flaws and fix them.

Future work includes defining a finger rest to provide movement along the vertical axis (z-direction) in order to support fulcrum with the upper jaw. Furthermore, measuring the physical properties of the human organs is key to improve the realism of haptic interaction. Finally, the second generation Haptodont system will be evaluated with dental students to examine the learning outcomes and quality of user experience.

(a) Healthy (no pocket) gingiva simulation (b) Abrupt pocket simulation



(c) Smoothed pocket simulation

Fig. 13. Various pocket configurations.

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