Adapting a Haptic Motor-Skill Simulator to Include 3D Histology and Supporting Information Architecture

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PROJECT RESEARCH

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SUMMARY

A recent prevalence of simulator technology in medicine brings about many obvious educational opportunities. Less obvious, perhaps, are the many opportunities presented in biomedical visualization, that is, model design and information architecture (IA) for instance. These features must be considered equal to technology when developing simulator experiences to ensure educational goals are maintained. These factors were brought into question when presented with the opportunity to create a new three-dimensional (3D) model for use in an existing haptic-based periodontal probing simulator. A 3D model of a mandibular section was sculpted with histological features in order to present clinically relevant gingival anatomy in context with motor-skill exercise. Yet providing visual detail without direction is inadequate for ensuring learning objectives are met. Furthermore, simplified models are needed in a haptic system to maintain uninterrupted performance; this means a loss of visual detail and material realism. To meet these challenges, the architecture of the system was designed to include additional approaches to the content supplementary to the procedural training. Although this project remains in the prototypical phase, it represents an increasingly relevant challenge to conserve and adapt existing simulator technology in line with systems advancements and research in learning. The 3D models and proposed architecture are intended to exhibit how, with proper integration, these attributes can alter a single-objective, procedural task trainer into a meaningful and relevant virtual-reality scenario.

I. INTRODUCTION

A. Overview of research problem

Periodontal screening involves probing the gingival tissue to assess periodontal health or disease. “Probing depth (is a) distance from FGM to the bottom of the sulcus or periodontal pocket” (Eke et al., 2015, p. 611). Erriu et al. (2015) note that “Measurements in vivo are affected by substantial uncertainty, owing, for example, to probe features, anatomic variations and operator’s skill. Inadequate reproducibility in periodontal probing may lead to diagnostic mistakes and inappropriate therapeutic decisions” (p. 743). Because the technique is central to clinical practice and disease diagnosis, it is crucial that every dental student and hygiene student is prepared to perform the procedure reliably.

PerioSim™ is a haptics-based simulation platform developed at the University of Illinois at Chicago School of Dentistry in 2007. The simulator was created as a response to the growing need for supplemental probing-procedure training for first- and second- year dental and hygiene students. The intention was to set forth and maintain a baseline standard so that all students are at the same preparedness level when advancing from manikin training to live-clinical-practice training for this procedure. During the initial trial, PerioSim™ was determined to be a potentially useful learning tool; however, inadequacies were observed in the realism of the model, specifically the gingival tissue (Steinberg, Bashook, Drummond, Ashrafi, & Zefran, 2007). Additionally, while the user interface (UI) does allow the user to zoom in and out, rotate the model, and adjust the opacity, the underlying structures are not represented in the model; these functions do not reveal any new information when used.

The visual shortcomings are primarily due to inherent technical limitations of the haptics platform, which can only run low-poly models and cannot express a high level of material detail, an acceptable trade-off for real-time simulator interaction. In haptics-based learning, performance is paramount as a detectable lag in tactile or visible feedback can cause frustration and disengagement, thereby inhibiting learning (Chen & Thropp, 2007). This scenario presents a challenge to design visually detailed, but computationally efficient 3D models. In computer-based learning, solutions for delivering curriculum can also be found in the architecture of the software. Well-designed architecture can also ensure the central, task simulator is supported rather than overshadowed. This project addresses these factors in the context of a periodontal-probing simulator.

B. Significance of the problem

Periodontitis is the most prevalent infectious oral condition today (Nazir, 2017). It is also entirely preventable with proper screening and treatment. Untreated, periodontitis can result in tooth loss. It is also shown to accompany other chronic illnesses suggesting a correlating adverse effect on other systems. Associated conditions include: cardiovascular disease, kidney disease, diabetes, and pre-natal risks (Nazir, 2017). “It was estimated in 2009 to 2010 that 47% of US dentate adults aged ≥ 30 years (representing ≈ 65 million adults) had periodontitis” (Eke et al., 2015, p. 612). In an extensive study on periodontal care, Ghotane, Harrison, Radcliffe, and Gallagher (2017) revealed that preventative maintenance and screening practices led to a 40% reduction in the need for surgery over a six-year period.

The UIC College of Dentistry is the largest in the state of Illinois with a steadily growing application rate from 466 in 2012 to 704 in 2016 (UIC College of Dentistry, n.d.). Implementation of a procedural simulator to support clinical practice could offer valuable reinforcement to the department's faculty and curriculum. Although PerioSim™ was found to be a useful training device for skill development in periodontal-pocket testing (Steinberg et al., 2007), it has yet to be utilized by the department due to recognized shortcomings in the 3D model. By equipping this simulator with an enhanced model and allowing the current literature to inform the delivery of the curriculum, this project aims to present a way to conserve and adapt academic resources and extract their potential to avoid obsoletion and enrich their function and usability.

II. LITERATURE REVIEW

A. Periodontitis

"Periodontitis is characterized by destruction of the supporting tissues of the teeth including gingiva, periodontal ligament, and alveolar bone, which is caused by uncontrolled host inflammatory responses to the pathogenic oral microbiota." (Ho, Lamont & Xie, 2017, p. 1). Specific recognizable histological features are associated with the pathology. These are outlined in Table 1.

Table 1 The histological lesions in gingivitis and periodontitis			
Initial 24 - 48 hours	Early 4-7 days	Established 2-3 weeks	Advanced
Gingivitis			Periodontitis
Localized to gingival sulcus and subjacent periodontal tissue	Localized proliferation of junctional epithelium and sulcular epithelium	Proliferation of junctional epithelium and sulcular epithelium; some loss of collagen, but no loss of attachment	Pocket formation, loss of attachment, collagen and bone loss: An imbalance in the host–microbial interaction heralds the transition from a successful defense to a destructive pathological reaction. There is also a reparative fibrotic response, which becomes more evident with time

Table 1. The histological lesions in gingivitis and periodontitis. Adapted from "A clinical guide to periodontology: Pathology of periodontal disease" by A. Hasan & R.M. Palmer, 2014. *British Dental Journal, 216*(8), 457. Adapted without permission.

B. Place in education

a. Medical curriculum

With the pass of each year, medical knowledge expands exponentially causing an ever-increasing responsibility to the medical curriculum (Drake, McBride, & Pawlina, 2014; Craig, Tait, Boers, & McAndrew, 2010; Cho & Hwang, 2013). As a result, more efficient and innovative delivery methods are needed to meet educational demands due to the resulting reduction on dedicated lecture and laboratory hours in many areas of medicine (Drake et al., 2014: Estai & Bunt, 2016; Turney, 2007). Integrating relevant, but sometimes neglected aspects of medical curriculum into clinical training is found to be an efficient way to reinforce learning and facilitate the transfer of knowledge for both areas of study. This tendency has been observed with anatomy and pre-clinical dentistry by Rafai et al. (2016), as well as to anatomy and radiology by Sheikh, Barry, Gutierrez, Cryan, and O-Keeffe (2016). In a study by Smith, Martinez-Álvarez, and McHanwell (2014) investigating how context affects perception in medical education, students reported hindrance to learning when there was “A lack of relevance or understanding as to why the material was important” (para. 26). Lazarus, Chinchilli, Leong, and Kauffman (2012) describe how putting basic science into a clinical context eases learning and assists in retention and transfer. Bergman, Van Der Vleuten, and Scherpbier (2011) point out that while clinical relevance is taught in foundational anatomy early on, basic anatomy is neglected in later years throughout the clinical curriculum. Estai and Bunt (2016) corroborated this idea when they identify vertical integration in the list of best practices in anatomy education. For this project, by depicting deep gingival anatomy along with surface anatomy, the learner will be allowed to explore the structures affected during the procedure. This interaction will not only reinforce the knowledge of the underlying anatomy, but it will also provide a level of clinical relevance.

b. Histology

The area of histology is another challenging aspect of the periodontal curriculum. Education in microscopic anatomy and ability to interpret histological slides remains fundamental for understanding cell and tissue organization, function, and pathology. Despite its significance, perceived importance of this subject notably lacks among dental students while perceived difficulty level was reported to be higher among the same group (Drake et al., 2014). Traditionally, hands-on lab instruction has been the primary means of teaching histology to students, however, direct observation of specimens under a microscope is time-consuming and burdensome to an already loaded medical curriculum.

Microscopic tissue examination remains the standard method of understanding the relationship between cells and tissues; their function and organization; and the pathophysiology of many disease processes taking place at this level. Conventional light microscopy remains the standard in dental curriculum, even though virtual microscopy has been shown to contribute to better learning outcomes teaching dental histology (Hande et al., 2017). Although the value of histology has not diminished, there is a trend in medical education to dedicate less time to its study (Zaletel et al., 2016). The bias is so pervasive that many medical departments have done away with light microscope training entirely. Consistent with this pattern is a diminishing attitude among students towards its importance, with a notably higher statistic for dental students as shown by Johnson, Purkiss, Holaday, Selvig, and Hortsch (2015), see figure 1. This same study showed that dental students reported higher levels of perceived difficulty than medical students both before and after receiving histology curriculum, see figure 2.

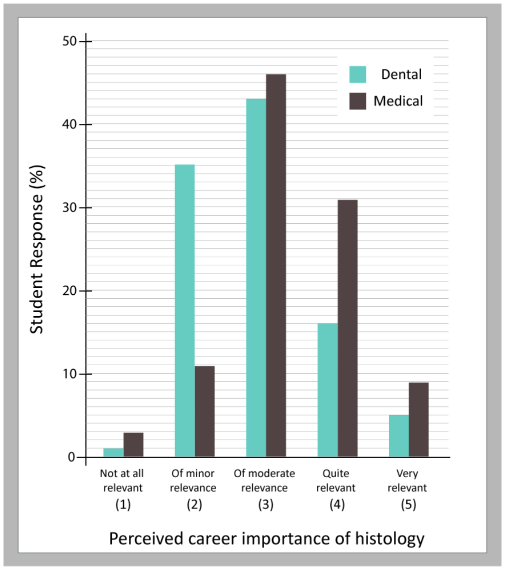


Figure 1. Perceived importance of histology for a career as dentist or physician. The bar graph depicts students' answers to the question 'How important do you think histology is for a future career in dentistry/medicine?' Based on a five-point Likert scale. Adapted from "Learning histology – dental and medical students' study strategies" by S. Johnson, J. Purkiss, L. Holaday, D. Selvig, & M. Hortsch, p. 67. Copyright 2014 by John Wiley & Sons Ltd. Adapted without permission.

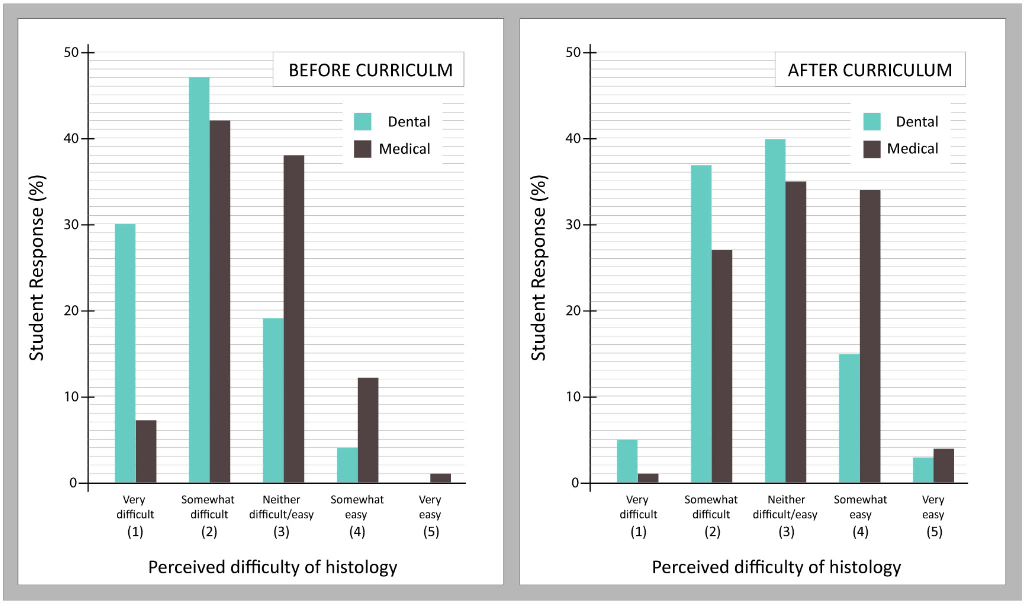


Figure 2. Students' view of histology as a difficult/easy learning subject. This bar graph shows students' views of histology as an easy/difficult subject BEFORE and AFTER completion of the dental/medical histology component. Students answers were based on a five-point Likert scale. Adapted from "Learning histology – dental and medical students' study strategies" by S. Johnson, J. Purkiss, L. Holaday, D. Selvig, & M. Hortsch, p. 68. Copyright 2014 by John Wiley & Sons Ltd. Adapted without permission.

c. Visuospatial ability and 3D models

According to Smith et al. (2014), anatomy students reportedly struggle with the 3D components of scale and orientation. Spatial ability is vital in the context of medicine for many reasons, one being that much of the data is extracted in this form. Take for example histology as well as imaging technologies such as x-ray, MRI, and ultrasound. A challenge noted with traditional histology is the interpretation of 3D structures from two-dimensional (2D) slices. The fact that the dental school entry exam includes a measure of the ability to interpret 2D representations of 3D objects indicates the importance of spatial ability in the field of dentistry. Interactive visualizations have been shown to “mediate the relationship between spatial ability and cross-section accuracy” (Berney, Bétrancourt, Molinari, & Hoyek, 2015, para.4). 3D visualization enables users to understand mass, direction and depth, otherwise difficult concepts when considering small features. Berney et al. (2015) proceed to explain how explicit, dynamic visual representations build better mental models thereby facilitating visuospatial ability. Yu and Berlew (2012) demonstrate how performance of an indirect hernia repair can be improved with the help of a conceptual aid, in this case a sushi roll, to provide a mental reconstruction of the 3D aspect of the anatomy of the inguinal ring. These examples show that better visuospatial understanding assists technique. An interesting study to note is that of Wu, Klatsky, and Stettan (2010) in their paper, *Visualizing 3D objects from 2D cross-sectional images displayed in-situ vs. ex-situ*, they conclude that delivering 2D CT data in place, on the object itself as opposed to apart from, “can facilitate the mental visualization of 3D structures” but that “spatial separation of exploration from the cross-sectional view was found to have a highly negative impact on user performance” (p. 58). Based on the cited research, it is not implausible to suggest that visualizing histological features in a dynamic 3D model used for technique development will facilitate conceptual understanding of the structures encountered, and that this understanding could have a beneficial effect on performance. Also important is the combination of 3D models within a haptic interface. Though it has been found that the ability to rotate and manipulate a 3D object improves structural understanding (i.e., Berney et al., 2015; Garg, Norman, & Sperotable., 2001; Huk, 2006), it was also reported that “for 3D models to be of educational value, students must be given tasks to perform that will force them to manipulate the data and explore the information before them” (Pujol et al., 2016, para.29). Given the significance of the histological features relative to the procedural task, a correlating education value is indicated.

d. Computer-based dental education platforms

Multiple inventive computer-based teaching aids have been created and received with good results, examples of which include: an interactive histological atlas (Rosas, Rubí, Donoso, & Uribe, 2012); gamified dental skill training to aid in mixing the alginate used for casting dental impressions (Hannig, Lemos, Spreckelsen, Ohnesorge-Radtke, & Rafai, 2013); e-learning modules of varying complexity (Woelber, Hilbert, & Ratka-Krüger, 2012); and VR haptic-based drill training utilizing schematic models (Al-Saud et. al., 2017). In the literature so far, there is no reference to a multimodal haptic platform for dentistry integrating e-learning architecture and histology such as this one. Further, motor-skill simulators generally tend to exist as a screen and a haptic controller with little regard to UI or IA and lack basic components such as an exit button or a feedback module. There are benefits to this, so as not to remove the learner from the virtual reality environment with the presence of UI elements, but it does limit the learner to that singular objective and does not allow for self-guided exploration.

C. Medical simulators

a. Simulation training

Many areas of medicine and public health are looking towards advancements in simulation for doctor and clinician training as it offers deliberate manual practice with the option to explore, make mistakes, and self-correct without the patient risk factor. Unlike real-world practice, computer-based simulators also offer the opportunity to augment reality and provide information beyond that which is available to the naked eye. Trey and Kahn (2007) stress that a principal advantage of computer simulations is to visualize invisible phenomena. Though the benefit of simulator training is well-documented (i.e., Cartier et al, 2016; Johnston et al, 2016, Michael et al., 2014; Teteris, Fraser, Wright, & McLaughlin, 2012), the rapid rise also brought about criticism that the dazzle of the technology was causing simulators to lose touch with the broader context of healthcare and instructional design that it was meant to facilitate (Kneebone, 2005). Satava (2009) stresses that simulators are a tool to enhance curriculum and not a goal unto themselves. For example, research reveals little educational difference between a bench-model wooden box and an immersive VR bronchoscopy simulated experience (Chandra et al., 2008). The examination, in turn, has caused a shift back toward a more critical evaluation of simulator design within the context of instructional design and cognitive theory (i.e., Chauvin, 2015; Fraser, Ayres, & Sweller, 2015; Rasmussen, Konge, Mikkelsen, Sorensen, & Andersen, 2015; Satava, 2009).

b. Haptics

Smith et al. (2014) designed to analyze what constitutes deeper learning in anatomy education, “A major factor...was being able both to see and feel structures in the practical” (Smith et al., 2014, p. 275). Haptics technology is acclaimed for adding a sense of touch to the virtual reality (VR) experience. The platform is indispensable for manual skill development because it integrates visual and tactile feedback with the repetitive practice needed to develop accurate technique short of patient risk—qualities conducive to surgical task training. However, the tool is not without limitations. When working in haptics technology, a more efficient model with a simplified, low-polygon mesh (< 45 k) and basic surface material is needed to accommodate the minimum required graphic and haptic frame rates needed for real-time performance feedback (Banerjee, Hu, Kannan, & Krishnaswamy, 2017). These constraints are due to the need for continuous collision detection in haptics technology which is costly to the central processing unit (CPU). Concurrently, on a separate loop, graphical rendering must constantly refresh to keep up as the model is manipulated, e.g., rotated, zoomed, in 3D space. Ensuring smooth, real-time visual and tactile performance feedback is paramount over the level of material realism because a lag in the system will quickly cause frustration and disengagement, thereby hindering learning (Kerwin, Shen, & Sterdney, 2009). “Visual update must be performed at least 30 Hz and haptic (touch) information must be refreshed at 1 kHz” (Halic, Sankaranarayanan, & De, 2010, p. 431). In regard to experiences in virtual reality, Chen and Thropp (2007) note an observable negative impact on psychomotor and perceptual task performance when the frame refresh rate drops below about 15 Hz. Though the tradeoff in visual fidelity has come to be recognized in haptic interfaces, it is not always accepted as shown by the number of research projects dedicated to finding ways around it. (Chan, Li, Locketz, Salisbury, & Blevins, 2016; Halic et al., 2010; Kerwin et al., 2009). The discussion brings about a question of the importance of visual fidelity in the simulator experience.

c. Simulator fidelity

The widespread adoption of simulation technology has naturally brought about an analogous body of research rooted in understanding what constitutes a useful simulation model. The dimensions by which others have suggested measuring simulation fidelity are multiple and varied. Having been described as physical, semantical, and phenomenal by Dieckmann, Gaba, and Rall (2007); and engineering, environmental, and psychological by Norman, Dore, and Grierson, (2012). Tun, Alinier, Tang, and Kneebone (2015) took these concepts and reframed a model specific to healthcare education using the terms: “patient, healthcare facility or environment, and clinical scenario” (p. 167). Tun et al. (2015) also provided the definition: “the degree of accuracy to which a simulation, whether it is physical, mental, or both, represents a given frame of reality in terms of cues and stimuli, and permissible interactions” (p. 164).

In a 2012 review of the subject, Norman et al. questioned whether high-fidelity models improve the transfer of learning better than low-fidelity models and found the net results unsupportive in the area of basic motor-skill and technical training. Similarly, Gu et al. (2017) reviewed this question concerning nontechnical-skill simulators (defined as decision making and situational awareness). Their team found low-fidelity simulators to be “non-inferior” to high-fidelity simulators in the learning outcome. The model for this project intends to satisfy both motor-skill and nontechnical skill categories. Despite the listed research that contends this fact, many maintain that a high-fidelity virtual environment will lead to better user engagement and therefore enhance learning (Kerwin et al., 2009). This school of thought tends to center on striving towards a “perfect simulation” defined as being indistinguishable from the phenomenon it simulates (Johansson, 2004). One could argue that the ability to zoom to 100 x magnification, adjust opacity, and view structures in cross-section, as in the case of this research project, takes reality beyond human reality and into a place where the imperceptible can be perceived, thereby, making the experience less true to reality. Because these features certainly provide a perceptible benefit, what then would be the purpose of remaining constrained by real-life representation? The conversation is complex and undoubtedly varies case-by-case. Given the inconclusive standing of the literature, it is hard to say where the model central to this research should fall on the fidelity spectrum, or even how this spectrum should read. With the uncanny computer graphic (CG) realism now seen in everyday applications such as video games and movies, the expectations to be “wowed” by perceived actuality is now commonplace. However, as Bowman and McMahan (2007) observe regarding medical simulators, “If all that these technologies provide for the user are oohs and ahs and a unique user experience, it would be difficult to justify the expense” (p. 36). Since this research focuses on learning objectives rather than entertainment value, we must think about how much this factor contributes to procedural training and contextualized anatomy learning. Because known limitations are set forth by the technology, and the effect of fidelity on performance is questionable, we will look to Dieckmann et al. who suggest: “When learning is the focus, the flawless recreation of the real world is less important. It is necessary to find situations that help participants to learn, not necessarily the ones that exactly mimic any clinical counterparts" (p. 191). That said, a comparison model will need to be created to evaluate the qualities of the haptics model against a more realistic looking 3D model to allow direct observation of the visual disparities between the two. From there we can investigate how these discrepancies might be met to achieve the learning outcomes set forth within the capacity of the haptics system.

D. Theoretical foundation

a. Constructivism

Building on Jean Piaget's educational philosophy of Constructivism, Jonassen and Rohrer-Murphy (1999) write about methods of designing learning experiences that facilitate knowledge construction. One way that he proposes to do so is to "stress the conceptual interrelatedness of ideas and their interconnectedness by providing multiple representations of the content to convey the complexity" (p. 224). By introducing detail of the underlying anatomy, the learner may perceive and better understand the underlying tissue structure and how this anatomy is affected by the probing procedure. This additional context introduces a new level of information in a meaningful way which, according to constructivist theory, should facilitate deeper comprehension. Alfieri, Brooks, Aldrich, and Tenenbaum (2011) confer this idea in regard to discovery-based education, "allowing learners to interact with materials, manipulate variables, explore phenomena, and attempt to apply principles affords them with opportunities to notice patterns, discover underlying causalities, and learn in ways that are seemingly more robust" (p. 1). Because this application will be in the context of a motor-skill training exercise, there are different factors to consider when deciding how to deliver the information. It would be a disservice to add visual detail which distracts from the central objective: procedural practice. Mayer's theory of cognitive load establishes that introducing extraneous information can be taxing on working memory and, therefore, detrimental to learning. Rudolph, Simon, and Raemer (2007) state, "If the goal is to develop kinesthetic awareness and muscle memory, high physical fidelity is desirable. Conceptual and emotional and experiential modes of thinking are secondary. It is important that the conceptual aspects of the simulation do not undermine or contradict expectations generated by the physical task." (p. 163)

b. Dual-task interference

Multiple learning tasks within the same platform are simultaneously demanding on both cognitive and psychomotor resources. This conflict presents the risk of dual-task interference, an established paradigm that describes the detrimental performance effect when multiple tasks compete for working memory. A thorough discussion of the background on this research is available in a review by Meyer and Kieras (1997). In the paper, the authors offer approaches for overcoming this tendency by establishing "supervisory control in cognition and action" (p. 20), which is to say, the architecture of how and when the information is presented. In this case, because the secondary task is visual, contextual, and does not compete for direct or immediate user input, it can be presented concurrently with the procedural task. However, because of the specific learning objectives outlined in this project, dedicated mechanisms are also needed so that the visual detail works as more than just passive context. Besides taxing cognition, there are also benefits to adding a secondary task because they can act as a gauge in determining skill proficiency (Haji et al., 2015). According to cognitive load theory, as a learner advances from novice to expert, the manual task will become autonomic allowing room for extraneous information processing. Fitts and Posner describe phases of learning, beginning with cognition - understanding the task; association - practice, reflection, and feedback; automation - the task can be performed with little cognitive input. Their theory of motor-skill acquisition holds that experts “see more” when performing at the automation stage. By allowing self-guided learning, trainees can allocate the extra level of information as dictated by their skill level.

Table 2 Fitts & Posner stages of motor skill learning			
Cognitive	Movements are slow, inconsistent, and inefficient. Considerable cognitive activity is required.	Attention to understand what must move to produce a specific result. Large parts of the movement are controlled consciously. Practice sessions are more performance focused, less variable & incorporate a clear mental image (technical/visual).	1: Essential elements were not observed or not present. (Early Cognitive)
			2: Essential elements are beginning to appear. (Late Cognitive)
Associative	Movements are more fluid, reliable, and efficient. Less cognitive activity is required.	Some parts of the movement are controlled consciously, some automatically. Practice sessions link performance and results, conditions can be varied. Clear Mental Image↔Accurate Performance	3: Essential elements appear, but not with consistency. (Early Associative)
			4: Essential elements appear at a regular satisfactory level. (Late Associative)
Autonomous	Movements are accurate, consistent, and efficient. Little or no cognitive activity is required.	Movement is largely automatic. Attention can be focused on tactical choices. Practice sessions are more results oriented. Focus is on greater range of motion, speed, acceleration & use of skills in a novel situation.	5: Essential elements appear frequently, above required level. (Early Autonomous)
			6: Essential elements appear continuously, at a superior level. (Late Autonomous)

Table 2. Fitts & Posner stages of motor skill learning. Adapted from *Human Performance* by P.M. Fitts, M.I. Posner, Belmont, CA: Brooks/Cole, 1967.

E. Architecture

a. Multi-tasking simulations

Being that most of the research for procedural-task training simulators tend to focus on the singular goal of task training, established models of our simulator experience—aimed at including an objective supplementary to task training—are scarce, so a complementary example was sought. A body of research centered on cognitive training within task simulators paralleled the multiple learning objectives of this research. Kahol et al. (2009) articulate a goal that resonates with this project, which is to realize the full potential of simulation by moving beyond sole psychomotor acquisition. Their team devised a methodology for multitasking simulations used to guide this project. Their model uses layered architecture consisting of a psychomotor component, an external component (or in this case additional visual information - the gingival anatomy), these two elements can be overlapping in a multithreaded manner or an independent manner. Kahol et al. (2009) suggest the following three modules: Sensory, the supplementary component; Simulation, multithreaded to incorporate the sensory module; and Feedback/evaluation, which presents information on user performance in which both tasks are reinforced, and reflection allowed. The model has been applied and reinterpreted for this project and is represented in figure 3.

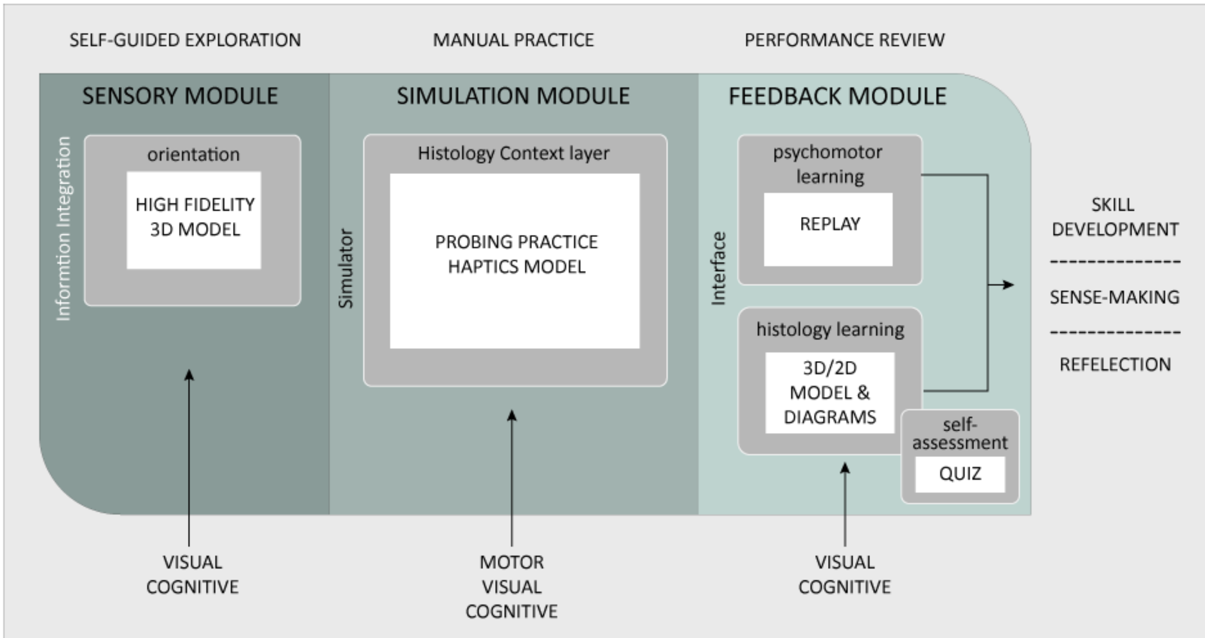


Figure 3. Methodology for cognitive simulator design. Interpreted from “Cognitive simulators for medical education and training” by K. Kahol, M. Vankipurama and L. Marshall, 2009, *Journal of Biomedical Informatics, 42*, p. 596. Copyright 2009 by Elsevier. Adapted without permission.

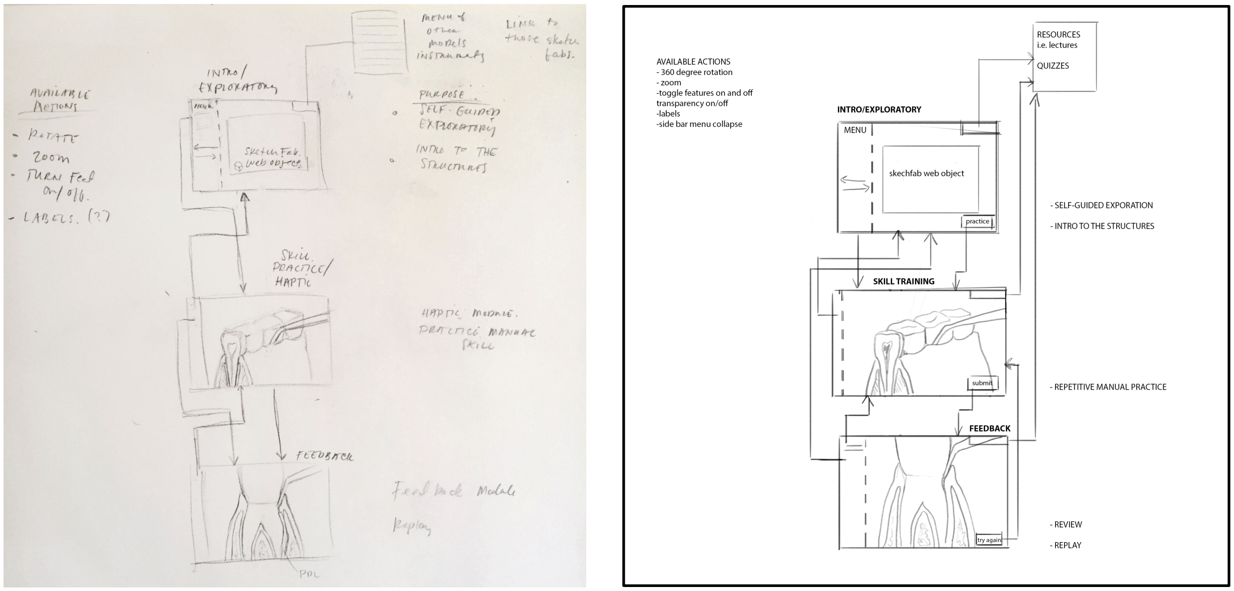


Figure 4. Information architecture development. Wire framing from sketch to legible sketch.

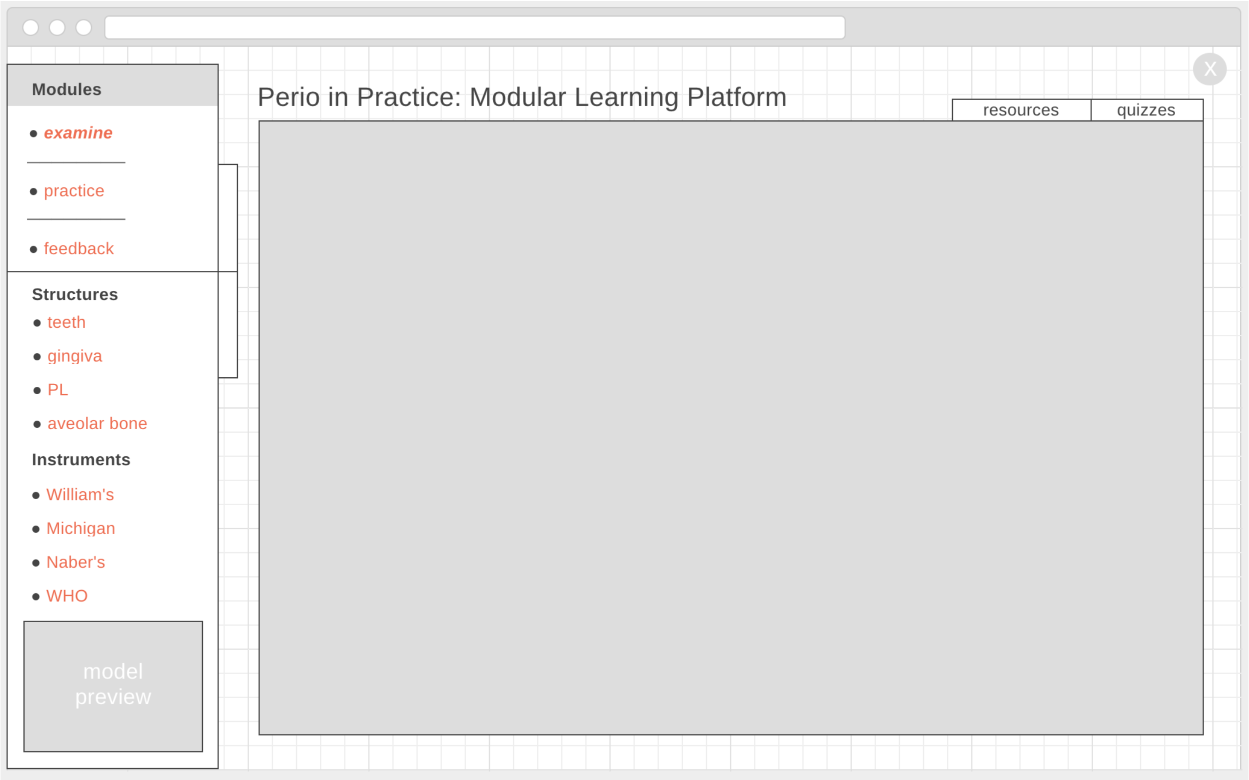


Figure 5. User interface. High-fidelity wireframe.

b. Implicit scaffolding

The usefulness of the added microscopic visuals will rely on a variety of interface design factors ranging from how and when they will be available to the user and how much control the user has when interacting with the information, as well as in turning the features off and on. Two critical findings outlined by Podolefsky, Moore, and Perkins (2013) are: “1) students build understanding through exploration and by drawing on prior knowledge, and 2) the design of the sim is critical to the learning process” (p. 5). Podolefsky et al. (2013) developed the implicit scaffolding framework for the PhET project at the University of Colorado, Boulder. The system focuses on interactivity design using “affordances, constraints, cueing, and feedback in order to frame and scaffold student exploration without explicit guidance, and it is a particularly useful design framework for interactive simulations in science and mathematics" (p.1). This model stresses the use of designing with "productive constraint" which provides visual cues of the intended interaction while constraining the interactivity to the affordances of the tool, in other words, the design will guide the correct interaction. While Podolefsky et al. (2013) outline a very robust framework, the learning objectives of this project are rather simple, so only some pieces will be applicable. Below is a list of some of the concepts derived from this work.

Table 3 Scaffolding to enable sense making	
Layout	Cueing to provide productive exploration
	If text is used, place short labels near object
Range of interaction Range of interaction (continued from previous page)	Constraints on the conceptual parameter space that students can explore, through selection of the boundaries of variable parameters (i.e., the value range of sliders)
	Encounter sets of pedagogically useful scenarios or cases that help learners recognize key relationships and make sense of concepts.
	Representations designed to be familiar and to draw on intuitive knowledge.
Feedback	Feedback that is readily interpretable and immediate allows for a seamless interaction, maintaining a mode focused on conceptual understanding rather than sim usage.

Table 3. Scaffolding to enable sense-making. Adapted from *Implicit scaffolding in interactive simulations: Design strategies to support multiple educational goals* by N.S. Podolefsky, E.B. Moore, and K.K. Perkins, 2013, Retrieved from https://arxiv.org/pdf/1306.6544.pdf. Adapted without permission.

c. Productive constraints

As outlined by Podolefsky et al. (2013), limiting the range of interaction is necessary for efficient learning, the following user constraints were determined based on evidence from the literature.

i. Appearance presets

While the inclusion of all of the layers of visual detail may seem conducive to a more thorough understanding, it can also act as a hindrance. Illustrators utilize a multitude of techniques and visual cues used to focus information that have come to be recognizable conventions While interactive mechanisms such as magnification and transparency sliders within the user's control may add a level of exploration, it also adds another level of complication to an already complex set of variables. The "range of interaction" principle set forth by Podolefsky et al. (2013) explains that allowing free range is not necessarily the most efficient way to learn. In this case, multiple transparency sliders would be required for opacity control on all of the various structures. While transparency can allow for a better spatial understanding of the underlying features relative to the surface, it can also be disorienting when structures overlap, and edges are lost. Granting full control would allow for a vast range of obscured in-between values that would not assist understanding. This type of interaction was determined to be non-productive; therefore, ideal transparency settings have been pre-defined with "on" or "off" being the two variables. The level of opacity of each structure will be guided by a hierarchy of depth as suggested by Viola and Gröller (2005) in their "Smart Visibility" guidelines.

ii. Key view

A "key view" is the point of view that provides the optimal amount of information. In a study investigating "how medical students learn spatial anatomy," Garg et al. (2001) found that when studying 3D anatomical objects, students tend to mentally record a viewpoint-specific 2D projection even when presented with the ability to rotate the model 180°. They also found that students spent more time with key views when studying the material, suggesting that certain viewpoints are more important than others for understanding anatomical relationships. Viola and Gröller (2005) further explain the value of the cutaway technique when visualizing volumetric 3D data, asserting that adopting existing visual arts techniques in a 3D environment makes for an even stronger representation than their static counterparts. For the model in this application, it was determined to have the model terminate in a cutaway aligned to the central plane of the second premolar, so the cross-sectional reference is always available and reinforces anatomical understanding.

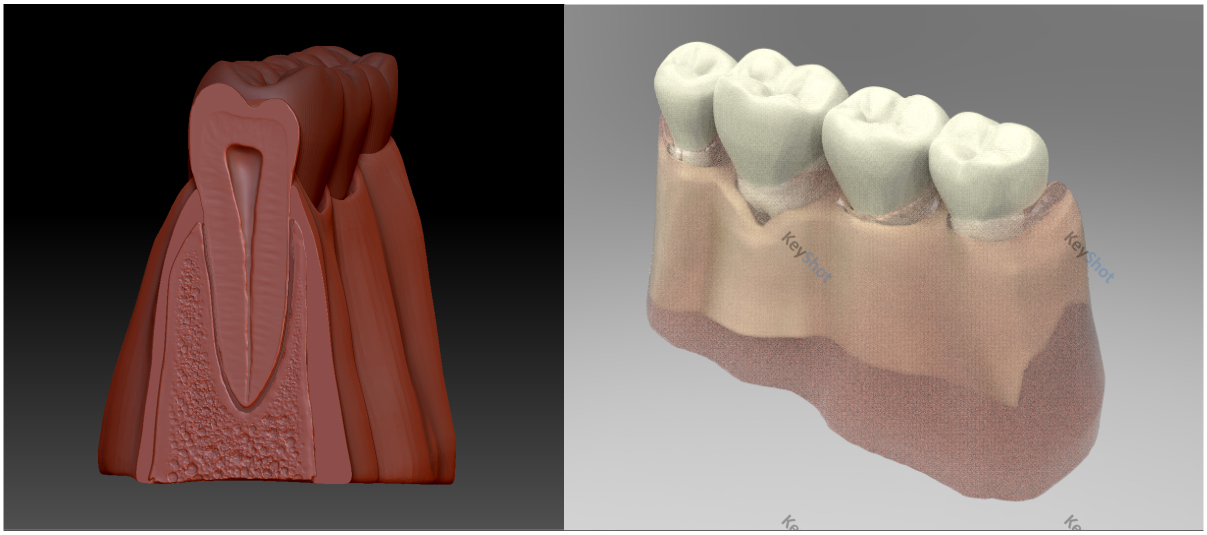


Figure 6. Appearance presets. Key view and transparency settings.

III. RESEARCH SIGNIFICANCE

A. Significance of research study

Despite the increasing prevalence of simulator training and research performed in this field, clear guidelines are lacking on 3D modeling for a haptic interface in which polygon and surface material constraints exist. Due to these constraints, the systems typically consist of a simplified model with the singular objective of task practice. This study addresses ways to expand a haptic experience by including a more detailed level of anatomical context, as well as multimodal architecture to add a level of exploration and learning reinforcement. The aim in doing so is to build upon the body of research informing simulator training visuals and to exemplify how a task training simulator might be renovated to become a more robust learning tool. It is hypothesized that visually representing the anatomy of the gingival tissue will allow students to appreciate the structures affected during probing procedure as well as reinforce histological understanding of the health and the disease process, in turn supporting the proper diagnosis of gingivitis or periodontitis. Merging multiple disciplines—clinical practice, applied anatomy, and histology—within a single learning module is intended to provide practical, cognitively efficient delivery of the curriculum.

B. Research questions

1. How does one develop a 3D model that incorporates detailed microscopic anatomy optimized for a haptics interface?
2. How does one best incorporate a secondary learning objective into a simulation device designed for motor-skill development?

IV. METHODS

A. Research study design

Validation was based on the satisfaction of the research committee. The objectives outlined in the research are as follows:

- Identify a research gap
- Model the following structures in 3D (both optimized and unconstrained)
  - ☐ four teeth
  - ☐ gingiva
  - ☐ periodontium
  - ☐ alveolar bone
  - ☐ probing instruments
- Build a prototype learning module according to guidelines set forth in the literature.

B. Stimulus design plan

This project is a collaboration between biomedical visualizers and periodontal faculty to envision an innovative approach to teaching preclinical periodontal education. The 3D models were designed under close advisory of periodontal faculty to support aspects of the periodontal curriculum for incoming students while keeping specific learning goals in focus. The prototype learning modules allow the research committee to interact with and compare the visual qualities of the model optimized for the haptic interface to the high poly model unrestricted by computational limitations. The learning modules also organize the material according to the instructional-design based information architecture as outlined. The prototype serves as a template for future implementation.

Deliverables supplied to the College of Dentistry include the haptic models (oral, and probing instruments) in .vrml file format for future C++ force feedback programming, the high-poly model for future implementation in VR, and the web-based learning modules which will be adapted as a stand-alone e-learning course complete with quiz sections.

a. Methods of production

i. Identifying essential features

Required features were identified based on their importance to the probing procedure. While some aspects of periodontal disease are recognizable at the gross level; it is important for students to understand the etiology of the disease resulting in the change in appearance. Rete pegs, for example, are found in attached gingival epithelium and result in a stippled-surface feature. This is important because its lacking is an indication of periodontal disease due to inflammation and loss of attachment. In contrast, a smooth appearance is seen on sulcular, junctional, and mucosal epithelium. Other features identified as essential for visualization in the model are: Tooth enamel, cementum, dentin; collagen fiber direction; biological width; cementoenamel junction; mucogingival junction. See figure 7.

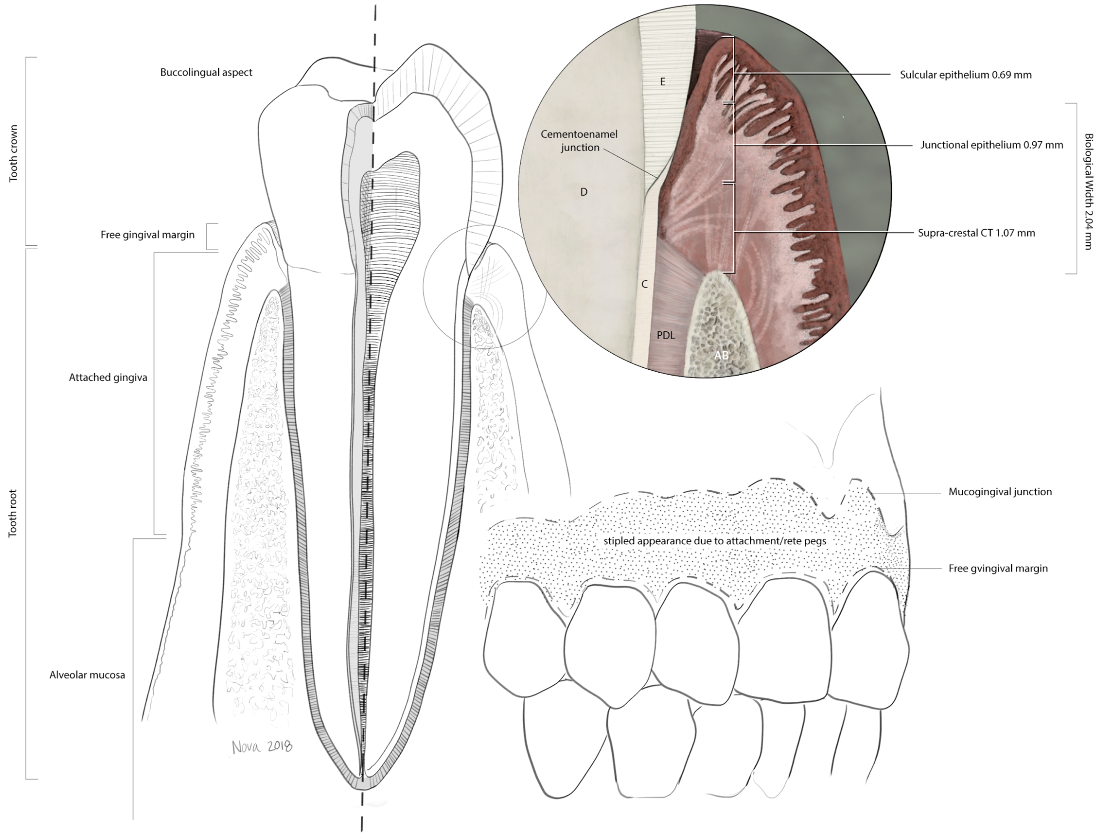


Figure 7. Essential anatomy and histology. 2D representation of features identified as important for the context of probing procedure. Author's illustration. 2018.

ii. Model production

Each subtool was duplicated and decimated to the lowest number of triangle polygons possible while still maintaining basic form. The decimated models were then divided up to the needed resolution for polypaint and texture. At the highest subdivision level, the divided mesh was projected onto the original high-poly quad mesh to regain detail. Each subtool was taken to the lowest subdivision level and cloned for UV unwrapping. The generated maps were copied and pasted onto the divided triangle poly mesh and at their highest subdivision level, using the multi-map exporter, normal, displacement, and bump maps were created from polypaint. The low-poly .obj was exported and opened in Autodesk 3DS Max. The maps were opened in Photoshop and the diffuse layer painted with schematic histological features. All assets were then brought into Autodesk 3DS max, checked, and exported as a .3DS file. the file type compatible with the Quick Haptics platform.

The existing low-poly 3D VRML files used in the previous PerioSim™ were provided and used as a foundation. The existing models expressed different states of periodontal disease, so they were revised to represent healthy tissue as determined by this project. Using Pixologic Zbrush, the models were retopologized from a low-poly triangle mesh to quads and then divided to over a million polygons, so detail could be sculpted. The open areas of the single-sided mesh were capped to replicate volume rendering. Anatomical reference was obtained from *Wheeler's Dental Anatomy, Physiology, and Occlusion* (Nelson, 2015). The following structures were created and kept as separate subtools, so that they could each be manipulated separately: mandible, teeth (3 molars, 1 pre-molar), gingiva, and periodontal ligaments. The second premolar was cut on the buccolingual plane, so a distal-aspect cross section is ever present for student reference. Similarly, one-quarter of the gingiva surrounding the third molar was cut, to view the histology of the periodontium in relationship with the tooth surface. The periodontal ligaments for each tooth were created as separate subtools so that appropriate force feedback could be indicated for this structure which is important for tactile detection in periodontal probing. Alveolar, spongy bone texture was sculpted on cross-sectioned bone planes. Pulp cavity and dentin details added to the cut plane of the second premolar.

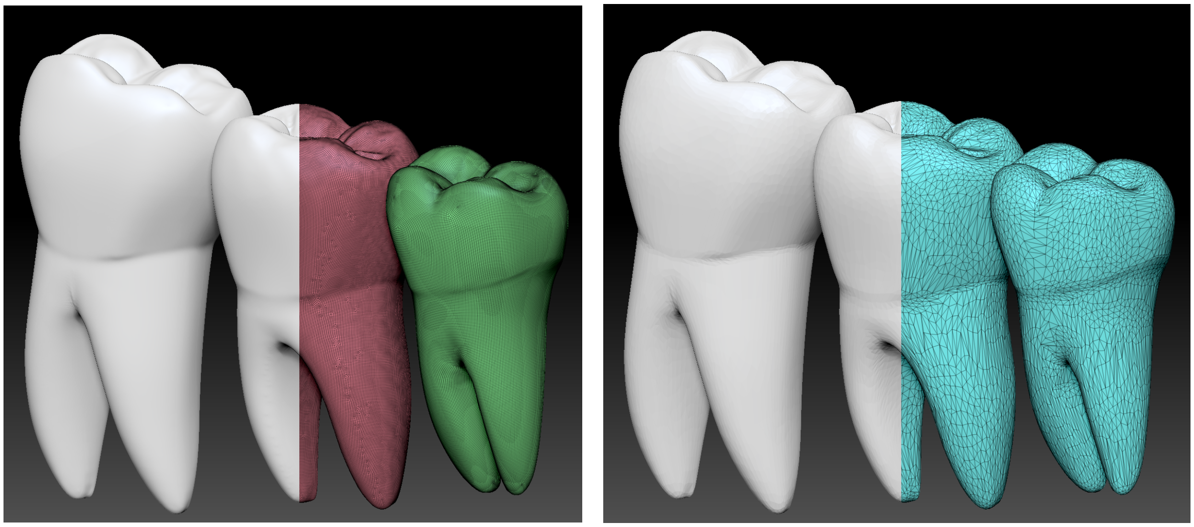


Figure 8. High-poly quads vs. low poly optimized resolution. A comparison of the surface effect of 354 K polygon mesh vs. 14 K polygon mesh.

The models were painted and textured using polypaint and spotlight paint to achieve more realistic tissue impression. Two methods of adding the histological detail were proposed. Projected histology and schematic painted histology (see figure 9). The schematic illustrated histology was chosen based on content-expert preference so that the features would be easy for first-year dental students to interpret.

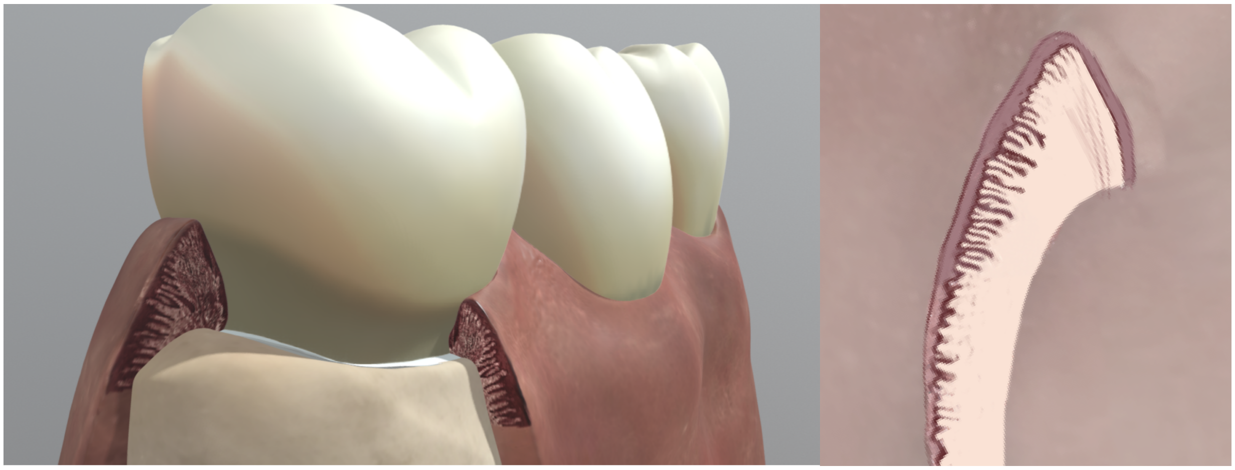


Figure 9. Realistic histology vs. schematic. Options for representing the histology to achieve ease of learning.

iii. Learning module production

The models were uploaded to Sketchfab using the Sketchfab-Zbrush plug in. The course modules were created in Articulate Storyline using web-object embedding for 3D model interaction and evaluation. Due to the scope of this project, the haptics module and feedback/replay portions of the course are in mockup phase for conceptual overview.

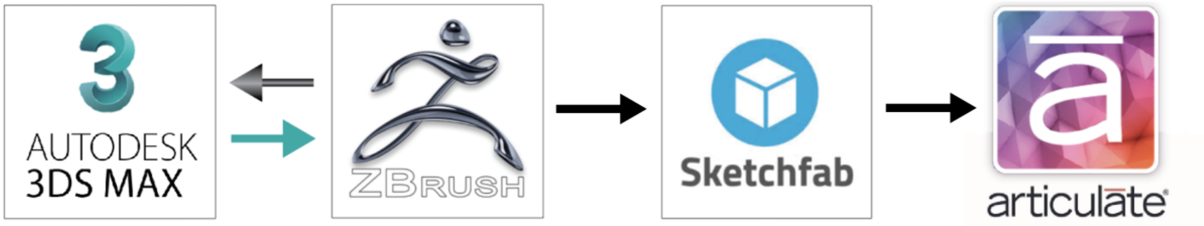


Figure 10. Software workflow. Methods of production from 3D model creation to model hosting and learning module build.

C. Evaluation plan

Although the human testing phase and analysis are beyond the scope and timetable of this research project, feedback from the research development team was used to inform visual decisions and approach.

a. Method of analysis

The prototype was presented to the research committee for evaluation. Satisfaction of the project committee measured qualitative success.

V. RESULTS

Seven models were completed including a section of, gingiva, mandible, bisected mandibular premolar, first, second, and third molars, and periodontal ligaments for each tooth. Maps and textures were created for ten instruments. The models and various iterations are available on the web via Sketchfab™ (www.sketchfab.com) at https://skfb.ly/6ypxT. The low-poly version of each model component and uv map (gingiva, teeth, bone) was brought into 3D Systems Inc. OpenHaptics, QuickHaptics™ software version to test mesh/map system rendering and compatibility.

A version of the learning module without the haptics practice and feedback components were made for use during the force-feedback programming phase of the application. The learning module is compatible for integration within Blackboard, UIC's learning management system. The SCORM packet will be uploaded to the online section of the periodontics course for introduction into the curriculum. The module includes a quiz section, glossary, and resources developed under the advisory of Dr. Ashrafi, director of the pre-doctoral periodontics department.

Comprehensive committee satisfaction was reached through assessment of the models via the prototype learning module hosted online at:

http://nbarto3.people.uic.edu/research/story_html5.html

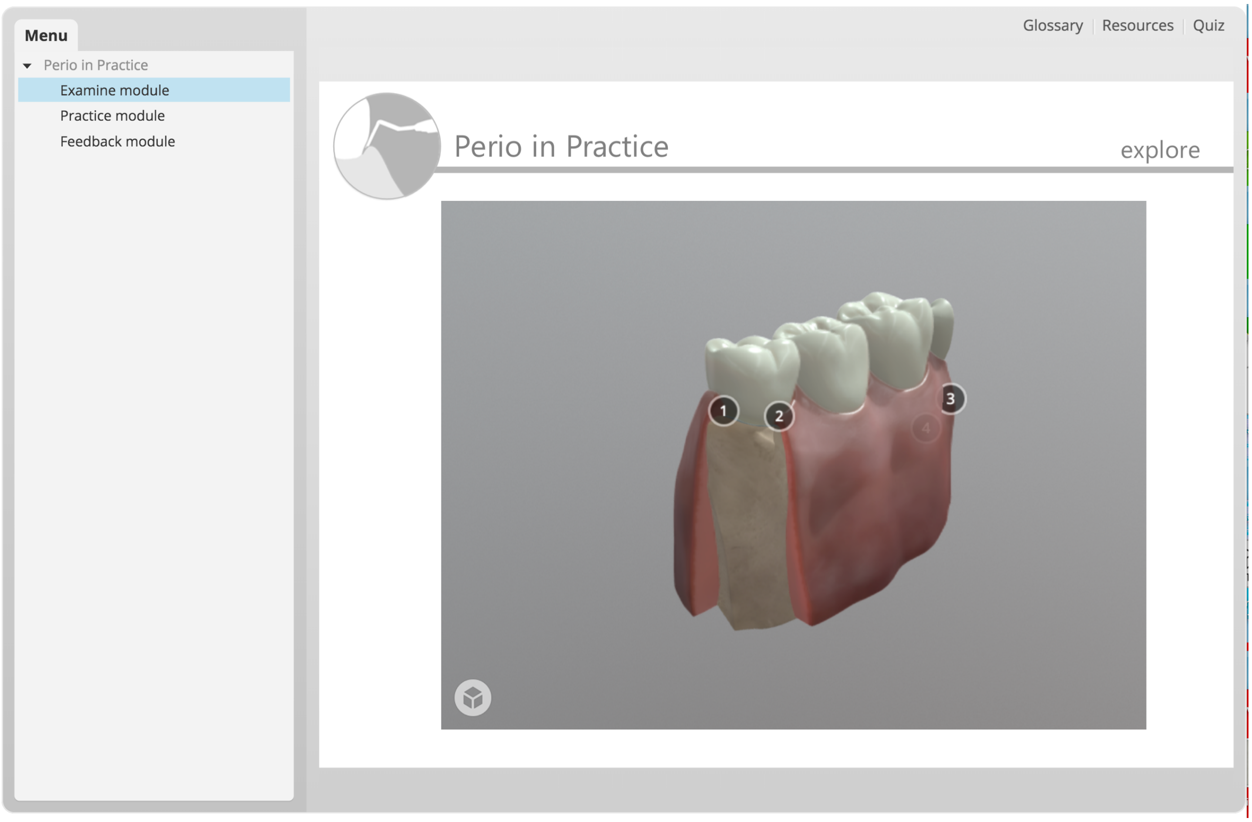


Figure 11. Active web-based learning module: Explore section. This component allows for self-guided exploration to prepare for practice. Identification of structures in 3D. Annotations provide a tour through key structures.

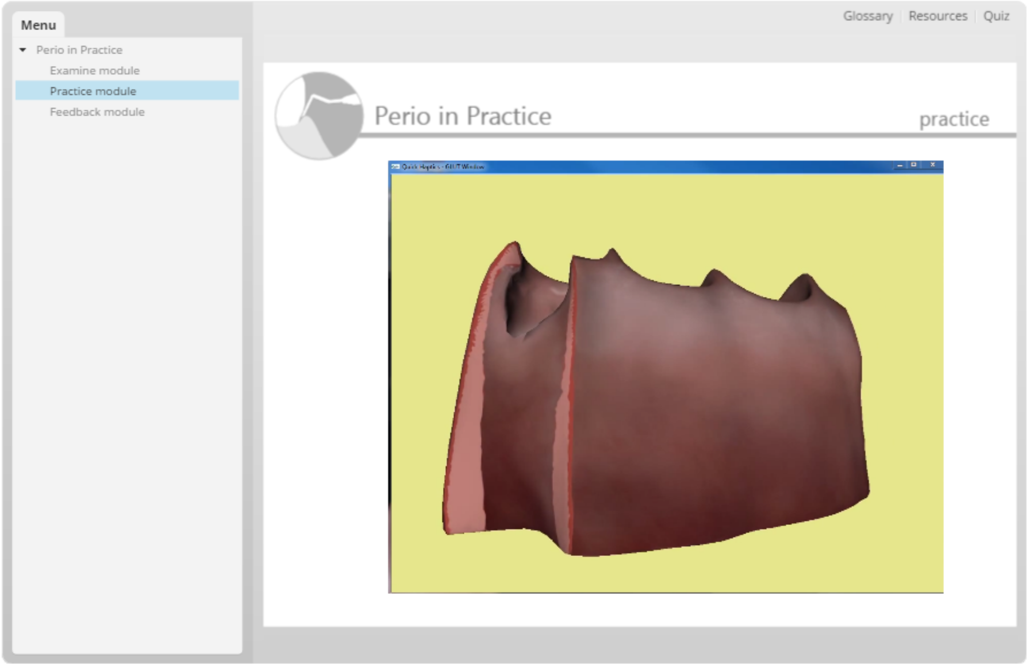


Figure 12. Active web-based learning module: Practice section mock up. Video taken from model uploaded to QuickHaptics™ platform. This section allows for periodontal probing practice.

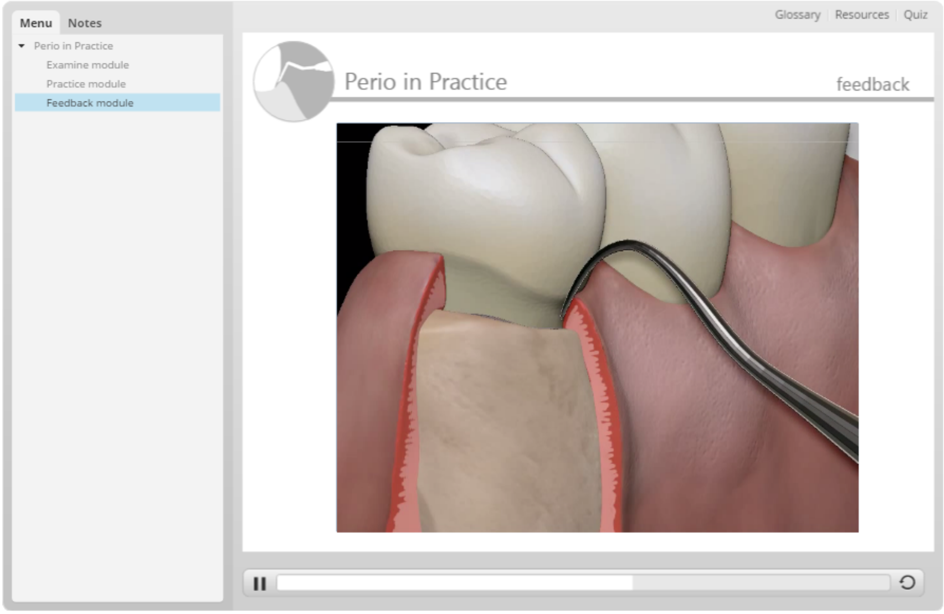
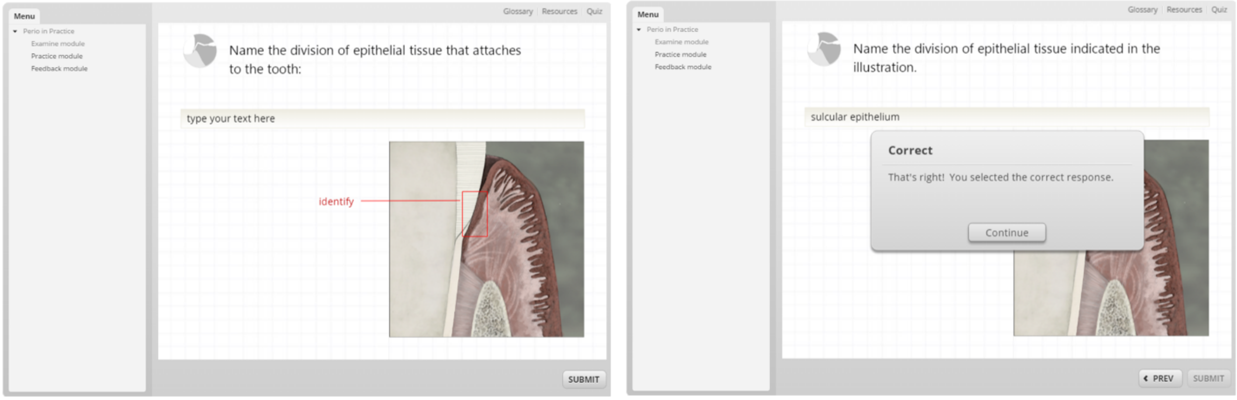


Figure 13. Active web-based learning module: Feedback section mock up. This section allows for review of practice performance. Replay of haptic interaction.



Name the division of epithelial tissue that attaches to the tooth:

type your text here

Name the division of epithelial tissue indicated in the illustration.

sulcular epithelium

Correct

That's right! You selected the correct response.

Figure 14. Active web-based learning module: Quiz section. This section allows for self-assessment. Including structure identification and knowledge check.

VI. DISCUSSION

A. Review of major points

Periodontitis remains to be the most pervasive oral health condition today. Because the periodontal probing technique is fundamental for disease diagnosis, it is integral for all dental and hygiene students to be adept at performing this procedure.

As a response to the ever-increasing demand for dental education, simulator-based education has become prominent in research and development, but technological advances do not necessarily add up to better learning outcomes. This research intends to examine ways in which motor-skill simulators can be reimagined to achieve a broader reach in education.

In this project, histological detail is represented in 3D to provide clinically relevant anatomy in context with a haptic probing procedure central to the platform. The two modalities, 3D model visualization, and force-feedback interaction are intended to provide to students, a holistic conceptualization of the procedure to support technique development and disease diagnosis. The 3D visualization of microscopic features allows for students to encounter the gingival anatomy in a new way intended to stimulate exploration and improved conceptual understanding. This project addresses navigating technical limitations when modeling for haptics by exploring how to work within these boundaries to add visual detail to a 3D model. Finally, this project examines a best-practices approach for delivering this curriculum in a multimodal learning module intended to support a thorough understanding of the probing procedure.

B. Limitations

At this stage, the haptics interaction is not yet programmed. Assessment is limited to conceptual and prototype-based.

C. Implications for profession

Given the pervasive use of simulators in medicine, biomedical visualizers are at the center of ensuring that 3D models and user interfaces are designed to utilize the virtual platform to the fullest. This research intends to exemplify how existing technology might be adapted to this effect. Modeling of histological features allows for direct observation of an often-overlooked component. The ability to explore and interact with features non-observable in practice provides the opportunity for more engaged, exploratory learning which could extend to any area of medicine requiring histological examination. Incorporating visually-amplified models and instructional design concepts in the creation of medical simulators may inspire new levels of expectation in simulator development and educational reach. It also demonstrates that a medical illustrator's contribution is equally important when developing a medical simulator platform.

D. Future applications

Although this project only covers healthy tissue, subsequent models of various periodontal disease states are planned. Additional features to support the virtual experience are also yet to be explored such as the addition of a fulcrum (finger rest) used to stabilize the clinicians' hand during periodontal instrumentation and promote proper hand technique, and visual cues to indicate improper technique, i.e., bleeding or color change. Additional structure for the learning module is also being considered, such as a tutorial page for the haptic module, and a quiz section to reinforce learning.

The intended audiences for this simulator are first- and second-year periodontal students training to achieve competence in the procedure before advancing to clinical practice with live patients. Both models, as well as the interactive prototype learning module, will be provided to the UIC School of Dentistry. Further development of the haptics platform to host the models and add force feedback is planned. Dr. Seema Ashrafi and her team will oversee implementing and testing in an overall validity assessment with qualitative analysis by the students and faculty at the UIC School of Dentistry. A pre- and post-test will assess the learning impact of the presented histology, while an opinion survey of the simulator experience will be used to evaluate impressions of the usability of the interface, clarity of information, model fidelity, and perceived confidence level. (See appendix for proposed questions and format). Once complete, the simulator could be made available as a teaching tool to this department and others outside of UIC.

While this research is relevant specifically to periodontics, 3D visualization of histology has the potential to inform many areas of medicine and future simulation experiences that could benefit from the incorporation of microscopic visual data.

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APPENDIX

A. Proposed questions for evaluation of visual assets

Likert-scale type:
1 = strongly disagree 2 = partially disagree 3 = neither agree nor disagree, 4 = partially agree, 5 = strongly agree.

- Would you recommend this to your students or colleagues? 1-5
- How satisfied were you with the quality of the model? 1-5
- Do you feel this tool provided a realistic representation of the teeth? 1-5
- Do you feel this tool provided a realistic representation of the gingiva? 1-5
- Did you consider the model to be a good representation of the gingival epithelium? 1-5
- Did you find the addition of microscopic anatomy useful? 1-5
- Did you find the addition of microscopic anatomy interesting/engaging? 1-5
- Do you think this is an effective training tool for learning pocket probing technique? 1-5
- Did you find this to be a helpful method of viewing histology slides? 1-5
- Did you find the simulator enjoyable to interact with? 1-5
- Do you think practicing with this simulator will improve your comfort with this technique? 1-5
- Do you think practicing with this simulator will improve your confidence? 1-5
- Would you want to use this tool again? 1-5
- Did having both slide and 3D histology examples assist understanding of the tissue structure? 1-5

Open ended questions:
- What did you like most about the application?
- What did you like least about the application?
- Which interactive features did you find most useful? Zoom, Opacity adjustment, rotation, magnification
- Did you find any of the visual elements distracting?