A Shared Haptic Virtual Environment for Dental Surgical Skill Training

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Abstract

Online learning has become an effective approach to reach students who may not be able to travel to university campuses for various reasons. Its use has also dramatically increased during the current COVID-19 pandemic with social distancing and lockdown requirements. But online education has thus far been primarily limited to teaching of knowledge and cognitive skills. There is yet almost no use of online education for teaching of physical clinical skills.

In this paper, we present a shared haptic virtual environment for dental surgical skill training. The system provides the teacher and student with a shared environment containing a virtual dental station with patient, a dental drill controlled by a haptic device, and a drillable tooth. It also provides automated scoring of procedure outcomes. We discuss a number of optimizations used in order to provide the high-fidelity simulation and real-time performance needed for training of high-precision clinical skills. Since tactile, in particular kinaesthetic, sense is essential in carrying out many dental procedures, an important question is how to best teach this in a virtual environment. In order to support exploring this, our system includes three modes for transmitting haptic sensations from the user performing the procedure to the user observing.

Index Terms: Applied computing—Education—Interactive learning environments Applied computing—Education—Collaborative learning Applied computing—Education—Distance learning Human-centered computing—Collaborative and social computing—Collaborative and social computing; Human-centered computing—Collaborative and social computing—Visualization—Visualization techniques; Computing methodologies—Modeling and simulation

1 Introduction

The high level and cost of resources required to provide clinical training in medicine and dentistry (e.g. over $350,000 per completing dentistry student in Australia in 2016 [15]) necessitates concentration of clinical training programs in relatively few universities in any given country. In low- and middle-income countries, these universities are typically located in the main urban areas, requiring those outside the urban centers to travel there for training. This is a particularly problematic constraint for continuing education in advanced techniques where not only equipment but also expertise may be scarce. In recent years, online learning has become an effective approach to reach students who may not be able to travel to university campuses for various reasons. Its use has also dramatically increased during the current COVID-19 pandemic with social distancing and lockdown requirements. But online education has thus far been primarily limited to teaching of knowledge and cognitive skills. There is yet almost no use of online education for teaching of physical clinical skills.

Virtual reality simulation is a promising approach to provide such online education for clinical skills. A number of virtual reality simulators already exist for dental skill training. These simulators allow a student to practice skills such as caries removal and access opening for root canal treatment by using haptic devices to control a virtual drill and mirror working on a virtual tooth model. VR simulators have a number of advantages over physical simulators (e.g., using plastic tooth replicas). They offer high-fidelity simulations that are reusable, hence less expensive in the long term, and can be configured to provide trainees practice on a variety of different cases. They also have the ability to record accurate data on individual performance, which provides the opportunity for trainees to practice independently and receive objective feedback, and to provide the data to educators for their assessment. Yet another advantage, which has not yet been explored for dental training, is the possibility of linking VR environments over a network so that a teacher and student may share a common environment.

In this paper, we present a shared haptic virtual environment for dental surgical skill training. The system provides the teacher and student with a shared virtual environment containing a virtual dental station with patient, a dental drill controlled by a haptic device, and a virtual drillable tooth (Figure 1). The teacher can demonstrate a procedure while the student observes, and the student can then practice the procedure while the teacher observes. Since the kinaesthetic sense (the sense of force and motion) is essential in carrying out many dental procedures [18, 21], and surgical procedures in general [16], an important question is how to best teach this in a virtual environment and how to make the haptic sensations "observable". In order to explore how best to communicate kinaesthetic information, our system includes three modes for transmitting haptic sensations from the user performing the procedure to the user observing: same force, opposite force, and delta force. The same mode transmits the force that the performer is exerting. The opposite mode transmits the force of resistance that the performer feels. The delta mode moves the observer's haptic device along the same trajectory as the performer's. The first two modes are designed to teach the amount of force to use, while the third is designed to teach the movement of the drill.

2 Related Work

A number of VR dental simulators have been developed as research projects and as commercial products [22, 24]. Probably the most sophisticated commercial simulators currently available are the Simodont [6] and VirTeaSy [3] systems. Both support training of the access opening stage of root canal and both provide haptic feedback. Simodont uses a 3D monitor as display, while VirTeaSy provides a kind of stationary AR to achieve hand/tool alignment. However, both systems lack any kind of shared virtual environment between student and teacher, and both have limited immersion by missing either stereoscopic vision or head tracking.

Several aspects of immersion and high levels of realism have been found to play an important role in training transfer, especially

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when learning motor skills [1]. Although studying the transfer of surgical training in VR is challenging, there is mounting evidence of the benefits of immersion and presence on the training effectiveness [4, 8, 9].

A recent study presented the system DenTeach for remote dentistry teaching. It is geared towards classroom-style teaching, where one teacher can instruct and supervise a number of students at the same time. In contrast to our system, it is not immersive and uses physical, artificial teeth. It provides software tools to assess some of the students' KPI's (such as burr velocities), and allows for offline training based on videos that include the teacher's tactile sensations. However, the handpieces cannot transmit forces from teacher to student or vice versa; they only can transmit vibrations from the teacher's hand-piece to the students.

Morris et al. [10] present a collaborative virtual environment for the simulation of temporal bone surgery. Their system is the closet to the approach taken in our work, in that theirs allows two users to independently observe and manipulate a common model, and it allows one user to experience the forces generated by the other's contacts with the bone surface (which is similar to the strategy 1 "*same*" in our system). The authors do not provide an evaluation of the performance of the system and the effectiveness of the system in skill training.

Shared haptic virtual environments have been explored earlier [27], however that work did not investigate teaching motor skills in VR. Panzirsch et al. [12] investigate a master-slave robot system with VR headset, and a light-weight robot for object manipulations.

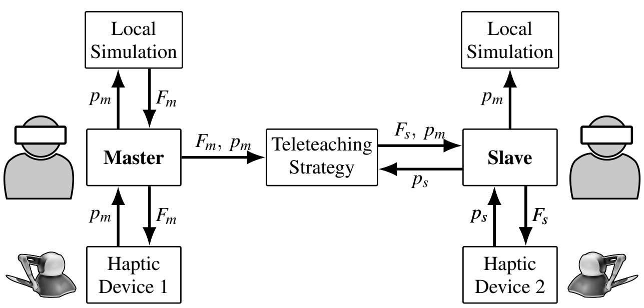

Figure 2: Overview of the shared environment setup for dental surgical skill training. Both systems perform local simulations. However, the master system controls the master and the slave simulation by sharing the haptic device position p_m. The haptic force of the slave system F_s is determined by the teleteaching strategy (see Figure 3 and 4 for details on the strategies we employed).

They investigated tele-presence, e.g., grasping objects with the robot hand, but not teaching motor skills in a teacher-learner setup.

The effects of latency between haptic VR systems coupled over long distances have been investigated by several researchers [11, 14, 25]. This and other work investigated effects and methods for mitigation of network latency that usually deteriorates the quality of the forces rendered at the "follower's" side. In this paper, we do not focus on this problem; instead, we assume for now that both systems are connected to the same local network, making the occurring latency negligible.

Instrument manipulation in dentistry requires proper application of force, as well as a proper orientation and trajectory of the instrument. A number of approaches have been taken to teach these aspects of dental skills in simulation. Kuchenbecker et al. [7] demonstrated how enhancing videos with one-dimensional pre-recorded vibrotactile feedback can improve the learning experience by providing new information to the student. Rhienmora et al. [13] presented a VR dental simulator that played a pre-recorded procedure while the student was required to align with and follow a ghost image of the instrument with their virtual drill, as well as to counter a force opposite to that applied. No evaluation was conducted. Su Yin et al. [19] presented an approach to using haptic feedback to train correct application of force in a dental VR simulator. For parts of the procedure where the force applied by the student was found to be too high or too low, the student was required to practice by applying an amount of force to cancel a prerecorded force exerted by an expert. Evaluation showed the approach to be effective in training correct application of force. The approach is similar to strategy 2 "*opposite*" in our study.

3 DESIGN

This section describes the system design, including the different strategies w.r.t. teaching the proper use of forces during the operation on the tooth.

3.1 Collaborative Setup

The dental instructor and student operate on separate and potentially distant computers (both have two NVIDIA CUDA capable GPUs). Each computer has a haptic device. (We use the 6-DOF Phantom Omni,which provides 3-DOF force feedback.) The master user can control both dental drills and the slave user has no control, but is instead rendered forces based on different strategies (see Section 3.2). The kind of forces rendered depends on the role. In order to achieve good immersion and, hence, a high level of presence for the users, we use head-mounted displays (HMDs) (we use the HTC VIVE Pro Eye) for the visualization of the correct user's perspective. An illustration of the setup can be seen in Figure 2.

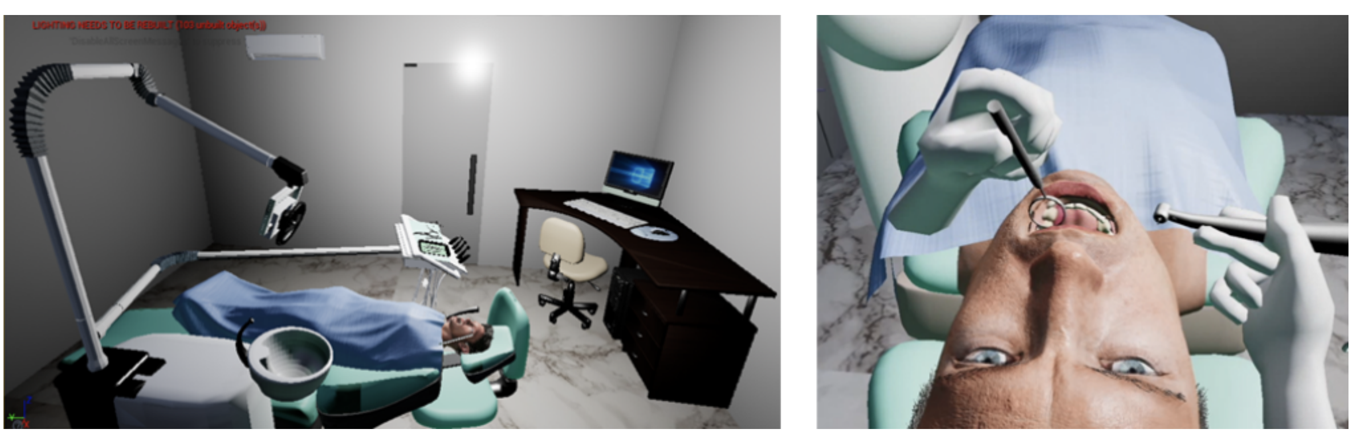

Figure 1: Our fully immersive dental simulator, including force-feedback for the tools. Both student and teacher share the same environment.

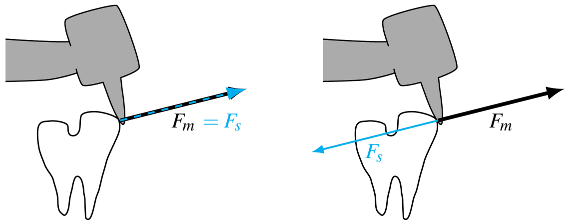

Figure 3: *Left*: Strategy 1 "*Same*": The slave system renders the *environment force* that the master system computed to the haptic device of the slave system. *Right*: Strategy 2 "*Opposite*": The slave system renders the inverted *environment force* that the master system computed to the haptic device of the slave system.

In teaching mode, the instructor is seated at the master system, which uses the traditional paradigm where physically-based contact forces that occur in the virtual scene are rendered to the haptic device. Thereby, the master user gets the impression of the real physical behaviour that would occur if they held the actual dental drill and came into contact with the real tooth. The student is seated at the slave system, which does not generate contact forces occurring from the student's interaction. Instead, the slave system renders a force that best conveys to the student what the instructor is doing, so that the student can learn the intricacies of the task.

In practice mode, the master system is occupied by the student and the slave system by the instructor. In this mode, the student practices the procedure and the instructor is being transmitted forces that convey the student behavior and the amount and direction of force that is applied; thereby enabling the instructor to feel the forces that the student is using. Next, we present methods that produce the forces for the slave system, which we refer to as teleteaching strategies.

3.2 Teleteaching Strategies

Since teaching through remote haptic rendering is not well researched, we selected three teleteaching strategies in order to explore the advantages and disadvantages of each.

Let F_s be the force that is to be displayed to the user at the slave side, and F_m the force that is computed based on the physically-based simulation on the master side (in world space). Let p_s and p_m be the slave's and master's target position of the center of mass of the virtual tool in world space. Let k be the virtual spring stiffness constant. Then our three strategies are:

1. "**Same**": $F_s = F_m$
2. "**Opposite**": $F_s = -F_m$
3. "**Delta**": $F_s = (p_m - p_s)k$

The goal of each strategy is to convey the haptic interactions that the instructor is performing and experiencing to the student. Ideally, the teleteaching strategy would simultaneously produce an *environment force* that renders the contact force exerted by the tooth, and a *guiding force* that would guide the student along as if the teacher were to guide their hand during a real operation [16]. However, this is not easily achievable, as these two types of forces need to be handled differently by the student. Therefore we chose to simplify the strategies by displaying only one of these forces at a time.

For strategies 1 and 2 we decided to produce the *environment force* that is generated by the physically-based simulation on the master side (see Figure 3). In both of these strategies, the student must hold the haptic device near the center of its work space, to avoid the work space limits. If the haptic device resides at any limit of its work space, a force towards the outside of its work space is no longer possible to render to the student in this way.

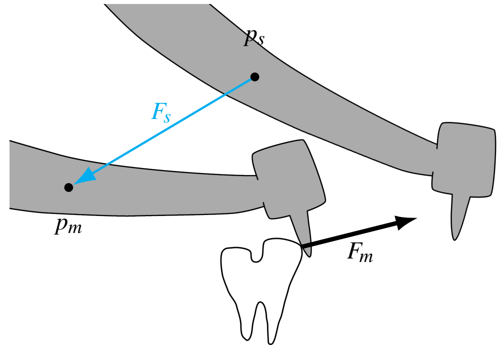

Figure 4: Strategy 3 "*Delta*". The difference of the tool poses is used to generate a spring force that will move the slave's haptic device towards the master's haptic device pose. This will ultimately make the haptic devices follow the same movement, therefore guiding the student's hand.

Strategy 3 (see Figure 4) produces the *guiding force*, as if a teacher were to push the student's hand along the trajectory that it should follow. The slave system might become unstable due to being overly sensitive to the spring stiffness k. Then it might become necessary to add a damping term to F_s:

$$F_s = (p_m - p_s)k - (v_m - v_s)\zeta \tag{1}$$

where v_m and v_s are the master and slave target velocities and ζ is the damping coefficient of the now dampened virtual spring. The *environment force* that is exerted from the tooth contact is not rendered here.

4 Methods

This section provides an overview of the methods used to create the collaborative dental training simulator. A core challenge in realizing virtual dental training is a simulation implementation that supports drilling at haptic rates of around 1000 Hz. We used a novel sphere-based simulation method that meets this requirement [5].

4.1 Simulation

We represent the tooth and drilling tool each by a set of non-overlapping poly-disperse spheres [26] called sphere packing (see Figure 6). The resulting data structure represents the complete volume of the tooth. In contrast, a 3D mesh only holds information on the surface structure, which can easily be extracted from the sphere packing as well. Therefore, the new representation is a superset of the 3D mesh. This allows us to easily compute *intersection volume* between the drill and tooth when they collide. Additionally, the tooth surface and volume can be updated at run-time by changing the sphere centers and radii or deletion. Consequently, the drilling simulations can be realized by updating the spheres.

4.2 Haptic Rendering

To display forces in a controlled manner to the haptic devices, the haptic rendering paradigm must be carefully designed with that in mind. We use the well-known proxy method to render forces that arise during the simulation on the master side. Our method is similar to that of Kaluschke et al. [5]. The virtual proxy follows the user's movement by being connected (conceptually) with a 6-DOF spring to the user's *target pose*, which is the pose in which the user is holding the haptic device. However, the virtual proxy is additionally constrained to the tooth's surface. Its point of contact on the tooth surface is determined by continuous collision detection between the virtual proxy and the *target pose*. The low-level communication

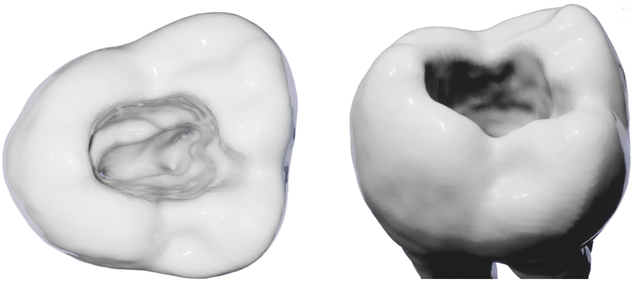

Figure 5: Tooth visualization during access opening stage of root canal procedure.

to the haptic devices is implemented using the open source library Chai3D [2].

On the slave side of the system, the simulation is synchronized by this target pose. The master system sends the most recent target pose in a continuous loop via UDP/IP connection. Both sides have an asynchronous thread that handles the network communication. The updates of the pose and force are implemented without locking by using double buffering. On the slave side, the retrieved pose is assigned to the local target pose and used in the local simulation. Since the simulation's only input is the tooth state and the target pose, no other method of synchronization is necessary between master and slave system. So far, we did not integrate any latency compensation, as we have only worked in a LAN environment. However, we plan to integrate movement prediction to minimize the error introduced by networking delay, such as methods developed for bilateral teleoperation [28]. Since we only use unilateral control, we might use a simpler predictor based on the last known pose and 6D velocity. Additionally, we might evaluate the teleteaching strategies in a simpler virtual environment, so that we can eliminate the physically-based simulation as a parameter to better focus on the differences among the strategies.

4.3 Visualization

Besides haptic feedback, dentists also heavily rely on visual feedback during surgery and, consequently, it is necessary during training to provide a correct visualization during the whole procedure.

The two procedures we are simulating are root canal access opening and caries removal. During the access opening stage of root

Figure 6: *Left*: The original 3D mesh of a tooth, used as the container to be packed with spheres. *Center*: Sphere packing ($\sim$ 400k spheres) of the container. This representation allows for fast parallel collision checks and physically-based simulation of the tool interacting with the tooth. It also enables the drilling simulation. *Right*: The implicit surface rendered using marching cubes, which can be updated in real-time during drilling.

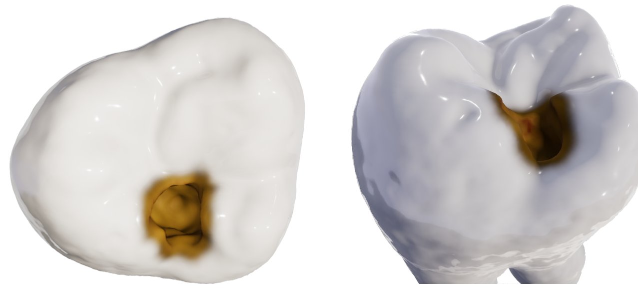

Figure 7: Visualization of the tooth during caries removal procedure. The brown colors visualize carious parts that need to be removed by the student.

canal treatment, the tooth material between occlusal surface and root canal needs to be removed in a cone shape (see Figure 5) so as to provide unobstructed access to the root canals for the next stages.

In caries removal, all carious parts need to be removed completely, while removing as little healthy tissue as possible [23] (see Figure 7). Since the carious part has color and hardness that are different from the healthy tissue, the dentist can rely on these to determine which part of the tooth is healthy and which is not.

So, in all procedures, we need to update the surface mesh of the tooth, including the telling colors (healthy, caries), in real time. Therefore, we implemented a marching cubes method on the GPU, with support for mesh smoothing and vertex colors. It can update the tooth geometry during normal interaction at a rate of roughly 10 Hz at a grid resolution of 200^3 (although the update rate is highly dependent on the drilling speed and tool movement speed; see below for details). In order to generate a new mesh from the updated sphere packing (modified by the drilling), we first need to convert the sphere packing into a distance field, from which we can then extract the surface mesh.

In detail, the method has the following steps:

1. Field Generation: Generate a scalar distance field based on the smallest distance for each and every voxel center to the spheres. In addition, the closest sphere associated with a voxel determines the voxel's color and a normal. The normal is later used to generate vertex normals for the mesh. Generating the normals at this stage is an optimization, since vertex normal generation on the mesh data has much worse performance. So, in total, we store two vector fields and one scalar field.

2. Smoothing: Smooth all fields (closest distance, color, normal) by bilateral filtering. This will remove bumps that could result from the underlying sphere representation. Additionally, the voxel grid is not as conspicuous after smoothing, thereby improving the visual quality of the mesh.

3. Marching Cubes: The smoothed fields are used to perform the marching cubes algorithm in parallel for each voxel. During the algorithm we do trilinear interpolation of the colors of the eight surrounding voxels to determine the vertex colors.

Step 1 is performed on the CPU, whereas steps 2 and 3 are performed on the GPU. Based on our experiments, this was the best performing solution since step 1 does not provide for enough independent tasks. There is a strong data hazard when parallelized by spheres, as each sphere will potentially write new distance values to all voxel cells in it's axis-aligned bounding box (AABB). Parallelizing over the voxels yields however worse performance, since the AABB optimization cannot be used. The spheres are relatively small, compared to the voxels, therefore processing all voxels inside the spheres' AABB does not need much computation time, and consequently, this optimization should be used.

We also implemented spatio-temporal optimization in our algorithm. We track the AABB of the tool movement, and only voxels inside that bounding box are considered for steps 1 and 2, with the rest using the previous value. Additionally, the triangles of each voxel are kept in a lower resolution grid that is a divisor of the voxel grid (we used 5^3 for 200^3). In step 3 we only compute the triangles for cells of the low resolution grid that were touched during steps 1 and 2. In the rendering component, we also divide the object into 5^3 meshes, each holding the triangles of a single low-resolution cell. Without these optimizations, the visual updates could not be done at run-time without significant delay or at a much lower voxel grid resolution.

4.4 Scoring

In order to evaluate our teleteaching method, we need to assess the quality of the outcome of the procedure performed by the student.

In general, the goal is to remove material from certain parts of the tooth, which we call the *target area* (e.g. carious tissue) while removing as little as possible of the other tissue, the *non-target area*. Consequently, we must specify, for both procedures, which parts of the tooth should ideally be removed and which should ideally be left intact.

Given this specification, it is easy to calculate the volume that was correctly removed and the volume that was incorrectly removed, and then evaluate it using a known similarity metric. We use the well-known DICE coefficient [17]. An overlap-based metric such as DICE is appropriate to use here since the overall shape of the tooth (such as contour and pose) remains unchanged and only small regions are altered by the user [20]. Our score s is then defined as

$$s = \frac{2 \cdot TP}{2 \cdot TP + FP + FN} \tag{2}$$

Here, TP, TN, FP and FN are the volumes of the four different classes of material:

- TP = number of unremoved non-target voxels
- TN = number of removed target voxels
- FP = number of unremoved target voxels
- FN = number of removed non-target voxels

Note that TN is not used in the score; we include it for completeness. The voxels are part of the same 200^3 voxel grid that is used for the visualization (details in Section 4.3, see Figure 8 for illustration).

During caries removal, the target area is the carious tissue, while non-carious tissue is healthy and should be left intact. For root canal opening, the classification is not as straight forward. Our solution is to let an experienced dentist perform the procedure as best as he can

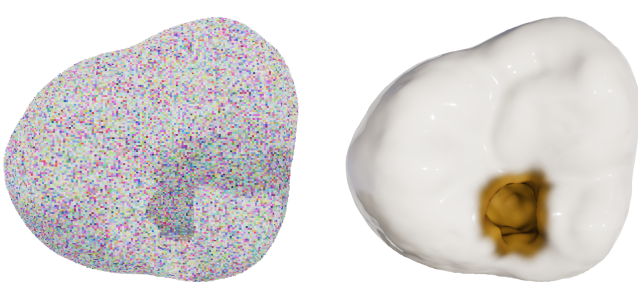

Figure 8: *Left*: Ground truth mesh. *Right*: The voxel discretization of the sphere representation. We use the voxel representation to extract and render the surface and to score the result. Here, each voxel cell is colored randomly to visualize the resolution.

and adapt the classification to that ground truth. The expert result is considered as the ideal result and therefore defines all still intact voxels as non-target and all removed voxels as the target area.

5 Evaluation Plan

We have obtained approval from the Institutional Review Board of Mahidol University for the evaluation study protocol. A randomized controlled trial with parallel groups will be carried out to determine the effectiveness of the proposed system in dental surgical skill training. We will recruit the volunteer subjects from third-year dental students who have experience using a dental hand piece in cavity preparation from the operative pre-clinical course. None of them will have received any skill training using a haptic VR system. The experiment will involve the comparison of skill achievement through outcome scores between three experimental groups and one control group. The experimental groups will be trained with the simulator using teleteaching with the three different teleteaching strategies: (i) same, (ii) opposite, and (iii) delta haptic training approaches; while the control group will be trained with the simulator using teleteaching, but without transmission of haptics. The task will be to perform caries removal on the provided virtual tooth. The overview of the experiment plan is shown in Figure 9.

Participants will first be briefly instructed on the use of the system and the requirements of caries removal after which they will use the simulator without teleteaching in order to familiarize themselves with the simulator interface. During the acquisition (training) sessions, the instructor will demonstrate the procedure from the master system while the participant at the slave system will be trained with different haptic force training or none. Each demonstration will be followed by the student's practice. In the practice session, the student will take control of the master system and the instructor will observe from the slave system. This demonstration-practice session will be repeated three times. The simulator will evaluate and log the outcomes prepared by the participants. The main outcome measure is the outcome score from each practice session. Standard descriptive statistics (means, standard deviations, medians) will be used to summarize the characteristics of participants in the study. The outcome scores of each training session within groups and between groups will be analyzed using statistical tests such as t-test and analysis of variance. After completing the acquisition sessions, we will ask the participants to answer a questionnaire on the realism of visualization, haptic rendering, and the effectiveness of the simulator in dental skill training.

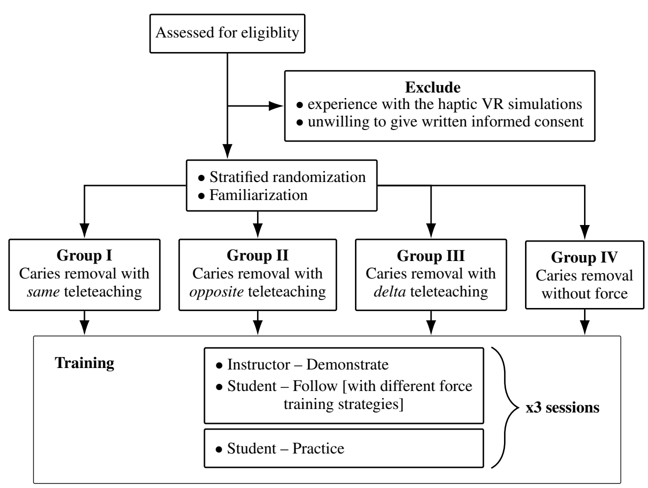

Figure 9: Experimental design for evaluation of the effectiveness of the teleteaching strategies

6 Conclusions and Future Work

We have presented the design and implementation of a novel shared haptic virtual environment for dental surgical skill training. The simulation design is driven by the demands of the application domain and makes use of a number of optimizations in order to provide the high-fidelity simulation and real-time performance needed for training of high-precision clinical skills. The simulation is general enough that it can easily be applied to other dental procedures that involve drilling, such as crown preparation and implant preparation. In addition, it could be applied in other domains such as orthopedic surgery.

To support exploration of how best to teach the use of kinaesthetic sense (force and motion), our design implements three strategies for teaching use of force and instrument trajectory. We have outlined the protocol for the evaluation, which will be done in the near future.

After completing our evaluation, we plan to replicate this setup and experiment with 6-DOF device output, i.e., with torque. We will also experiment with other teleteaching strategies, such as combining environment and guiding forces. We also plan to investigate new data-structures to parallelize the scalar field generation (see Section 4.3) in the visualization algorithm as well, by solving the previously mentioned data hazard.

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References

[1] D. A. Bowman and R. P. McMahan. Virtual reality: How much immersion is enough? *Computer*, 40(7):36–43, 2007. doi: 10.1109/MC.2007.257

[2] F. Conti, F. Barbagli, R. Balaniuk, M. Halg, C. Lu, D. Morris, L. Sentis, J. Warren, O. Khatib, and K. Salisbury. The chai libraries. In *Proceedings of Eurohaptics 2003*, pp. 496–500. Dublin, Ireland, 2003.

[3] J. Cormier, D. Pasco, C. Syllebranque, and R. Querrec. Virteasy a haptic simulator for dental education. In *The 6th International Conference on Virtual Learning ICVL*, pp. 61–68, 2011.

[4] S. Grassini, K. Laumann, and M. Rasmussen Skogstad. The use of virtual reality alone does not promote training performance (but sense of presence does). *Frontiers in Psychology*, 11:1743, 2020. doi: 10.3389/fpsyg.2020.01743

[5] M. Kaluschke, R. Weller, N. Hammer, L. Pelliccia, M. Lorenz, and G. Zachmann. Realistic haptic feedback for material removal in medical simulations. In *2020 IEEE Haptics Symposium (HAPTICS)*, pp. 920–926, 2020.

[6] P. Koopman, J. Buis, P. Wesselink, and M. Vervoorn. Simodont, a haptic dental training simulator combined with courseware. *Bio-algorithms and med-systems*, 6(11):117–122, 2010.

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

[8] K. Logishetty, W. Gofton, B. Rudran, P. Beaulé, and J. Cobb. Fully immersive virtual reality for total hip arthroplasty: Objective measurement of skills and transfer of visuospatial performance after a competency-based simulation curriculum. *J Bone Joint Surg Am*, Mar. 2020. doi: 10.2106/JBJS.19.00629

[9] K. D. Martin, C. C. Akoh, A. Amendola, and P. Phisitkul. Comparison of three virtual reality arthroscopic simulators as part of an orthopedic residency educational curriculum. *The Iowa orthopaedic journal*, 36:20–25, 2016.

[10] D. Morris, C. Sewell, N. Blevins, F. Barbagli, and K. Salisbury. A collaborative virtual environment for the simulation of temporal bone surgery. In *International conference on medical image computing and computer-assisted intervention*, pp. 319–327. Springer, 2004.

[11] S. Niakosari and S. Sirouspour. Improving transparency in network-based haptics. In *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 547–552, 2009. doi: 10.1109/WHC.2009.4810885

[12] M. Panzirsch, B. Weber, L. Rubio, S. Coloma, M. Ferre, and J. Artigas. Tele-healthcare with humanoid robots: A user study on the evaluation of force feedback effects. In *2017 IEEE World Haptics Conference (WHC)*, pp. 245–250, 2017. doi: 10.1109/WHC.2017.7989909

[13] P. Rhienmora, P. Haddawy, S. Suebnukarn, and M. N. Dailey. Intelligent dental training simulator with objective skill assessment and feedback. *Artificial intelligence in medicine*, 52(2):115–121, 2011.

[14] C. Schuwerk, X. Xu, and E. Steinbach. On the transparency of client/server-based haptic interaction with deformable objects. *IEEE Transactions on Haptics*, 10(2):240–253, 2017. doi: 10.1109/TOH.2016.2612635

[15] L. Segal, C. Marsh, and R. Heyes. The real cost of training health professionals in australia: it costs as much to build a dietician workforce as a dental workforce. *Journal of health services research & policy*, 22(2):91–98, 2017.

[16] L. C. Skoczylas, E. B. Littleton, S. L. Kanter, and G. Sutkin. Teaching techniques in the operating room: the importance of perceptual motor teaching. *Academic Medicine*, 87(3):364–371, 2012.

[17] T. J. Sørensen. *A method of establishing groups of equal amplitude in plant sociology based on similarity of species content and its application to analyses of the vegetation on Danish commons*. I kommission hos E. Munksgaard, 1948.

[18] A. D. Steinberg, P. G. Bashook, J. Drummond, S. Ashrafi, and M. Zefran. Assessment of faculty perception of content validity of periosim©, a haptic-3d virtual reality dental training simulator. *Journal of Dental Education*, 71(12):1574–1582, 2007.

[19] M. Su Yin, P. Haddawy, S. Suebnukarn, H. Schultheis, and P. Rhienmora. Use of haptic feedback to train correct application of force in endodontic surgery. In *Proceedings of the 22nd International Conference on Intelligent User Interfaces*, pp. 451–455, 2017.

[20] A. A. Taha and A. Hanbury. Metrics for evaluating 3d medical image segmentation: analysis, selection, and tool. *BMC Medical Imaging*, 15, 2015.

[21] G. Thomas, L. Johnson, S. Dow, and C. Stanford. The design and testing of a force feedback dental simulator. *Computer methods and programs in biomedicine*, 64(1):53–64, 2001.

[22] A. Towers, J. Field, C. Stokes, S. Maddock, and N. Martin. A scoping review of the use and application of virtual reality in pre-clinical dental education. *British dental journal*, 226(5):358–366, 2019.

[23] M. J. Tyas, K. J. Anusavice, J. E. Frencken, and G. J. Mount. Minimal intervention dentistry — a review*: Fdi commission project 1–97. *International Dental Journal*, 50(1):1–12, 2000. doi: 10.1111/j.1875-595X.2000.tb00540.x

[24] D. Wang, T. Li, Y. Zhang, and J. Hou. Survey on multisensory feedback virtual reality dental training systems. *European Journal of Dental Education*, 20(4):248–260, 2016.

[25] D. Wang, K. Tuer, M. Rossi, L. Ni, and J. Shu. The effect of time delays on tele-haptics. In *The 2nd IEEE Internatioal Workshop on Haptic, Audio and Visual Environments and Their Applications, 2003. HAVE 2003. Proceedings.*, pp. 7–12, 2003. doi: 10.1109/HAVE.2003.1244717

[26] R. Weller and G. Zachmann. Inner sphere trees for proximity and penetration queries. In *2009 Robotics: Science and Systems Conference (RSS)*. Seattle, WA, USA, June 2009.

[27] R. Weller and G. Zachmann. User performance in complex bi-manual haptic manipulation with 3 dofs vs. 6 dofs. In *Haptics Symposium*. Vancouver, Canada, Mar. 2012.

[28] X. Xu, B. Cizmeci, C. Schuwerk, and E. Steinbach. Model-mediated teleoperation: Toward stable and transparent teleoperation systems. *IEEE Access*, 4:425–449, 2016. doi: 10.1109/ACCESS.2016.2517926