A Virtual Reality Simulator for Training Endodontics Procedures Using Manual Files

Tales Bogoni*
Mato Grosso State University, Brazil
Medicine Assisted by Scientific Computing

Roberta Scarparo
PUCRS University, Brazil

Márcio Pinho
PUCRS University , Brazil
Medicine Assisted by Scientific Computing

ABSTRACT

This paper describes a virtual reality simulator for training endodontics operations using manual files. The simulator consists of a custom 4DOF haptic device for tracking and force feedback. The built device can simulate the kinematic behaviour of the files during endodontic surgery. During the simulation, the movements the user does with the manual files are tracked and at the end are displayed by a custom-made visualization tool. This tool shows the forces applied during the procedures, the direction and the amplitude of the movements and the final result of the tooth preparation. Preliminary tests showed that the level of realism of the simulator is satisfactory and the visualization tool allows for obtaining relevant data for a qualitative analysis of the procedures performed on the tooth.

Keywords: Endodontic training, haptic device, virtual reality in health training.

Index Terms: Virtual reality, visualization, haptic interfaces, force feedback, biomedical engineering education.

1 INTRODUCTION

Endodontics is the speciality in odontology that treats diseases that occur inside the root canals of the teeth. An endodontic surgery is basically divided in three parts: coronary opening, root canal preparation and obturation. In the first part, an opening is made on the tooth's crown so that the root canals can be accessed. Secondly, the canals are widened so as to remove the affected dentine layers and model the canals into a conical shape to receive the obturation material. In the third stage, the canals are filled with a given sort of obturation material and the tooth is sealed.

The second stage is the subject of this paper. In this stage, also known as Root Canal Preparation (**RCP)**, small calibre manual tools – named manual endodontic instruments or endodontic files – are employed. This stage is responsible for extracting the dental pulp and widening the root canals, removing thin dentine layers. This requires the dentist to manipulate the endodontic files in the appropriate manner, so as to prevent them from breaking or leaving portions of the tooth untreated. Manipulating these tools demands great motor ability and tactile sensitivity from the dentist, given that it is not possible to see the results of the treatment during its execution.

Practical training for endodontics professionals is carried out with human, animal or resin teeth. Due to the great variety of characteristics and pathologies that can affect root canals, students are often deprived of the opportunity to practise all necessary techniques, on account of the lack of teeth. Furthermore, training is done in a non-uniform fashion, for there are no two identical teeth, and treating a tooth renders it unusable. This leads to the necessity of obtaining large amounts of teeth for treatment, which is not always feasible.

One proposal to solve these problems is the utilisation of Virtual Reality (VR)-based simulators using haptic devices. With these simulators, it is possible to create tooth models that have the necessary characteristics for training, allowing students to be uniformly trained as well as to repeat the procedures until they achieve the required skill. Moreover, simulators make it possible for teachers to supervise the students' handling of the instruments, thus aiding in the assessment of their technique.

Aiming at providing these professionals with a low-cost VR simulator for endodontics training, this paper presents a simulator prototype with a haptic device and a Virtual Environment (VE), developed using a Novint Falcon Controller device adapted to supply users with 4 DOFs to manipulate the files, therefore permitting three-axis translation and rotation around the file's axis to be executed. Additionally, the simulator has a data visualisation tool that exhibits the movements performed by the user and allows the results of tooth preparation to be observed.

Next, this essay will present the kinds of movement that can be performed with endodontic files, as well all related work and a description of the simulator's build. Subsequently, both the simulator evaluation method and the visualisation tool will be described.

2 ENDODONTIC FILE KINEMATICS

Endodontic files are fragile instruments that must be handled appropriately, for they can break inside the root canals and cause as severe effects as the loss of the tooth.

Movement performed with such files, also know as 'kinematic movement'[1], is carried out in order to remove small dentine fragments from within the tooth and must be done in a way to not strain the files, preventing them from breaking.

Kinematic movement is classified into three kinds: back-and-forth, rotation and oscillatoty. In back-and-forth action (Figure 1-A), the file is inserted into the root canal towards the apex of the tooth (tip of the root) until it reaches the dentist's desired working length, at which point dentine is removed by forcing the file onto one of the canal's walls. This motion must be performed several times, until the entire diameter of the canal is filed. Rotation (Figure 1-B) consists of turning the file in a clockwise direction so that it penetrates the canal, increasing the working length. The oscillatory movement (Figure 1-C) consists of both clockwise and anticlockwise quarter-turn rotations. This movement has the same goal as rotation, though it does not wear the file down as much.

3 RELATED WORK

For this research, IEEE, ACM and PubMed digital libraries were queried, attempting to identify work about simulation in endodontics using haptic devices and to characterise what devices and interaction techniques were in use.

With respect to the utilised devices, the Phantom haptic device, with 6 DOF for tracking and 3 DOF for force feedback, was found to be the prevailing choice to control rotating instruments for coronary opening [2][3], to simulate both the usage of the odontological mirror [4] and periodontical procedures [5] [6] .

*tales@unemat.br

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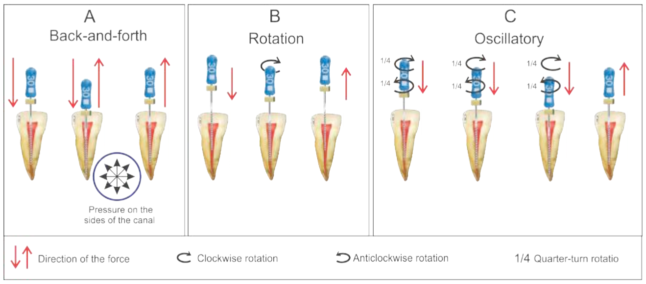

Figure 1: Kinematic file movement

In the specific area of endodontics, only work on file deformation and tooth pulp behaviour analysis was found. Tsao and colleagues [7], for instance, propose a new haptic device to identify the curvature of an endodontic file when inside a root canal and the force applied by the user when moving the file. Min Li and Yun-Hui Liu [8] present tests with new simulation methods for the interaction of endodontic files with the tooth's pulp using a robot.

During this research, no paper was found directly concerning the simulation of procedures with manual files for dentists' training.

4 Simulator Prototype

The simulator developed for this project is composed of a 4-DOF haptic device and a Virtual Environment that simulates the commonest procedures involved in RCP.

4.1 Hardware

Simulating endodontic procedures with manual files requires the utilisation of tracking devices capable of at least 4 DOF. Among them, 3 are related to the file's translation inside the tooth, and the fourth refers to tracking the file's rotation around its longitudinal axis. Besides tracking, it is important to provide the user with force feedback for all available DOFs. Out of the tracking devices available in the market, only those of higher cost, such as Sensable Phantom Premium and Force Dimension Omega 6, provide force feedback for the rotation axis. Since one of the goals of this simulator is to have a low cost so it can be widespread throughout odontology schools, usage of high-cost equipment is not feasible. Hence, an adaptation for a 3-DOF commercial haptic device was chosen instead. The designated device was a Novint Falcon Controller, which comprises 3 DOF for both tracking and force feedback.

The first step in adapting the device was positioning it vertically, since this is the main axis of movement during endodontic treatment. It was also necessary to devise a support on which the user's hand could lie during simulation (Figure 2). Such a support serves as a stand for the dentist's fingers, who, when performing real treatment, places them on teeth on either side of the one being treated and executes short vertical, lateral and rotation movements with the file. This stand also allows the dentist to apply traction to pull the tool out of the tooth. To this end, an opening with 3cm in diameter was made on the upper segment of the stand that secures the device, making way for file translation. After repositioning the Falcon, a modification was made to enable the endodontic file to be connected to the joystick. This was achieved by employing a plastic cylindrical adapter (Figure 3-A) that replaces the Falcon device's original handle. An aluminium axis was then attached to the adapter (Figure 3-B), having on its extremity a handle that mimics that of an endodontic file.

In order to track the file's rotation, the adapter has a sensor on the inside (Figure 3-C), capable of measuring the angle of rotation around the file's longitudinal axis.

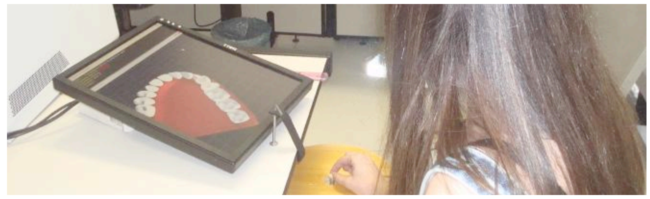

Figure 2: Simulator setup

Looking to generate force feedback with respect to the file's rotation, an SG90 TowerPro servomotor-controlled brake was installed (Figure 3-B), connected to an Arduino board. This force feedback is necessary to simulate situations in which the file is tightly placed or stuck inside the canal, requiring the dentist to apply greater force to rotate it.

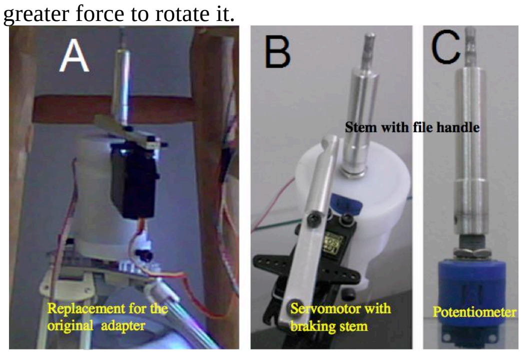

Figure 3: Adapter for manipulating and tracking file rotation

4.2 Software

The proposed virtual environment presents to the user a dental arch, the work file and the tooth on which simulation will occur. The dental arch is stored simply as a set of polygons, since its sole purpose is visualisation and does not take part in haptic simulation. The tooth under treatment, on the other hand, is modelled volumetrically with a resolution of 128x128x128 voxels. Voxels are classified according to their type of material, which can be enamel, dentine or pulp, bearing that each material resists uniquely to perforation and removal. The active (cutting) part of the file is also modelled volumetrically, with a resolution of 11x11x80 voxels (Figure 4). The remaining parts are modelled as polygons.

To allow file operation to be simulated, procedures for collision detection, force feedback calculation, and tooth tissue erosion are necessary and described over the next sections.

4.2.1 Collision Detection and Force Feedback for Translation

In order to support material removal, it is necessary to detect collisions between the file and tooth walls. The method used for collision detection and force feedback for translation is based on a previous work[9]. In short, collision detection is performed in two stages. In the first one, we check if the tip of the file is inside the bounding box of the tooth. If it is, the collision verification is carried out between each voxel of the file and tooth.

For calculating the force feedback for translation we use the god-object approach[9]. In general terms, the method takes a vector V_{force} (Equation 1) from the position of the haptic device (HIP-*Haptic Interface Point*) [11], to the last position of the virtual file(*Proxy*), multiplied by K_{voxel}, a constant that represents the material rigidity(Equation 2).

$$V_{force} = Proxy - HIP \quad (1)$$

$$F = V_{force} * K_{voxel} \quad (2)$$

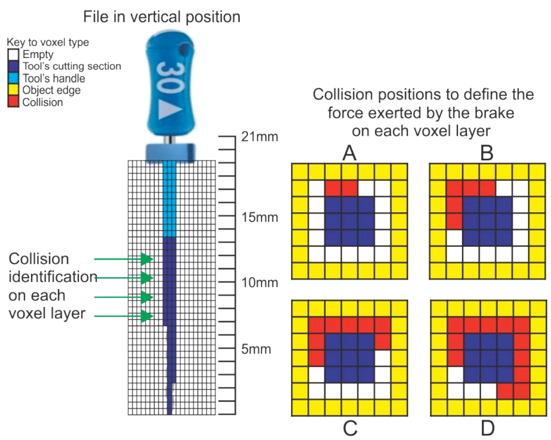

Figure 4: Collision detection for file rotation

4.2.2 Force Feedback for Rotation

The existing methods are capable of calculating force feedback with respect to file translation, but not rotation.

The method designed for this simulator evaluates which file voxels are colliding with the tooth and so calculates the force to be generated so as to brake the rotation. This is achieved by longitudinally sweeping the file for each of its voxel layers in search of those that are colliding with tooth voxels. Depending on the number and position of the colliding voxels, the brake is activated, producing smaller or greater resistance to the rotation. Figure 4 illustrates how collision detection is used to calculate the force feedback that will be generated for the rotation. On the left, the file is shown positioned vertically, along with the cutting section voxels, which remove material, and the handle voxels, which do not and are therefore disregarded. For each voxel layer, the tool's voxels are checked for collision against those of the tooth.

In light of the servomotor's force generation capacity, 4 different levels of force can be produced to resist movement. In image 'A' of Figure 4, only one side of the tool is colliding with the tooth's voxels, in which case the brake is triggered to produce level 1 resistance, the lowest one. In 'B', two sides collide, so the brake is activated to produce more friction (level 2) and consequently more resistance. The same happens in 'C' and 'D', in which even more resistance is produced.

4.2.3 Voxel Removal

In order to simulate the tooth's gradual wear, the system calculates the force exerted by the file on the voxels and progressively reduces the density of those that are in contact with the file. Therefore, the more the user scrapes the file on a voxel, the more its density is reduced, until it is completely eliminated from the tooth model.

Voxel density reduction takes place when the user performs rotation and oscillation movement and when pulling the file out of the tooth in back-and-forth movement. In back-and-forth movement, density reduction takes into account the direction vector of the applied force, i.e. if the file is being pressed to the right and upwards, the voxels on the right will suffer greater reduction than those on the left. In rotation and oscillation movements, the density of the tooth voxels touching the file is reduced equally for all voxels in contact.

The wear coefficient (α, in Equation 3) is proportional to the length of Vforce, limited to the maximum force feedback value supported by the haptic device (d_{max}). Equation 4 shows how the wear coefficient is used to reduce the voxel density(D), also taking into account the file's rigidity(K_{file}).

$$\alpha = |V_{force}| / d_{max} \text{ ; if } (\alpha > 1.0) \text{ then } \alpha = 1.0 \quad (3)$$

$$D_{new} = D - K_{file} * \alpha \quad (4)$$

Since the voxel has a density value that represents the resistance of the tooth's materials, the greater this value is, the more operations on the voxel will be required for it to be eliminated. This is so because the tooth is composed of three kinds of material, with distinct degrees of resistance: enamel, which is harder, dentine, which has intermediate rigidity, and pulp, which presents little resistance.

5 PRELIMINARY ASSESSMENT

In order to test the simulator, 12 subjects with experience in endodontics, among students, lecturers and professional dentists, performed RCP simulation on a lower-left premolar tooth, which presented a single root and a straight canal. The participant had to consider that the tooth had been diagnosed with symptomatic irreversible pulpitis and required endodontic treatment. During the tests, users were asked to carry out all necessary operations to prepare a real tooth, considering the opening of the crown to have been previously made.

The setup used to execute the tests comprised a desktop computer with an Intel Core i5 3.5GHz and an Nvidia GT620 graphics chipset. For visualisation, a 14" LED display was used, with a resolution of 1024x768 pixels, positioned horizontally on the desk (Figure 2). During the tests, data was collected every 25ms, including the file's movement, the force applied upon the haptic device, the type of kinematics employed, the file's rotation and the force feedback on it. This data was stored in log files for posterior analysis. Each test lasted approximately 23 minutes. With regard to the refresh rate of the haptic device, in all tests executed, 708,408 log events were generated, of which 99.96% reported the refresh rate to be steadily above 1KHz. To allow performed procedures to be visualised during simulation, a visualisation tool was created and is described next.

6 SIMULATION VISUALISATION TOOLS

For endodontic treatment to be carried out appropriately, it is necessary for all canal walls to be treated homogeneously and widened without affecting its original shape. Incorrect treatment on one of the walls of the canal may render it thinner than the others, which may even cause the tooth to break. Regarding this feature as a requirement, the visualisation tool was designed in a way to provide for the evaluation of the following items: homogeneity of treatment on the inner walls of the canals, amplitude of the movements and of apical pressure and final shape of the treated tooth.

6.1 Visualisation of the Homogeneity of Treatment on Inner Walls of the Canal

In order to identify whether or not the user employed appropriate and homogeneous lateral pressure on all walls of the canal during simulation, the force vector applied by the user when handling the haptic device is displayed. Figure 5 illustrates two users' simulation with the same file. On the leftmost simulation, the user can be perceived to have neglected treatment on some walls while applying excessive force on others. The rightmost simulation, on the other hand, shows that all walls have been treated and the user has exerted virtually the same force throughout. Considering that the canal of the tooth in question is straight and conical, the simulation on the right can be inferred to have left the canal uniformly dilated, whereas the simulation to the left would have created greater erosion on one side of the canal, causing change in the original shape. The simulator also enables visualisation of the final shape of the tooth, as described in section 6.3.

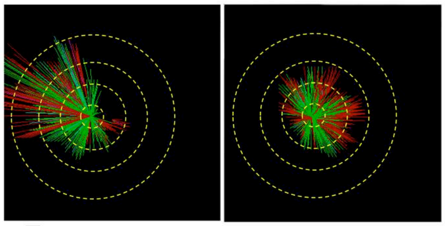

Figure 5: Direction and amplitude of the force applied

6.2 Amplitude of Movement and Apical Pressure

Other important factors in the analysis of endodontic procedures relate to the amplitude of movement and to the force applied on the tooth's apex (apical force). In the first case, if low-amplitude movement is executed, only part of the canal will be treated and the remainder may be contaminated. In the second case, should excessive apical force be applied, the apex may be perforated, leading to drastic clinical conditions in the future, including loss of the tooth.

Figure 6 presents the result of four simulations. In simulation A, the user performed short manoeuvres, leaving the upper canal untreated. In B, treatment occurs throughout the entire canal, though excessive apical force is applied, which can perforate the tooth's foramen. In simulation C, back-and-forth movement can be more clearly perceived, even near the apex. Finally, in D, there were predominantly rotation and translation movements close to the apex. Furthermore, it is possible to identify the amount of movement performed based on the number of lines drawn.

6.3 Final shape of the treated tooth

Another problem in real endodontic treatment is assessing the final result. One possibility is to make use of computerised microtomography, one before preparation and one after it. However, due to the great amount of radiation emitted by the equipment and to the difficulty in aligning the two exams, this approach can only be used on extracted teeth. With the simulator, it is possible to analyse the amount of wear caused onto each voxel. To aid in visualisation, the tooth model is segmented into slices, which are displayed individually in two-dimensional space, immitating tomography. Figure 7 shows the tooth's dentine in white, the original anatomic shape of the canal in green, completely removed voxels in red and reduced-density voxels in black, in the centre of the tooth. In practice, red and black voxels indicate the part of the tooth that was treated. The image on the left shows that the canal had its geometry altered, indicating that material was removed from some sections more than from others. Erosion occurred more uniformly in the image to the right.

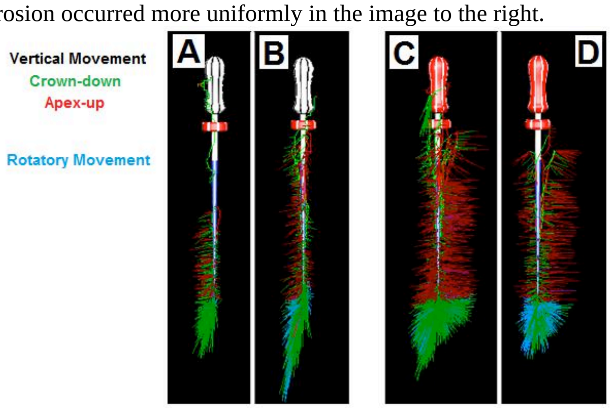

Figure 6: Amplitude of vertical motion and apical force

Figure 7: Final simulation result comparison

7 Conclusion

This paper has described a simulator designed for the training of endodontic procedures. With the simulator, odontology students can practise and follow their performance with a visualisation tool. This tool shows the force employed by the dentist during simulation, as well as the amplitude of movement, the directions in which forces were applied and the final result of the simulation, displaying the initial anatomical shape of the tooth and the changes that occurred throughout the simulation. During tests carried out with users, the system proved itself stable in refreshing the haptic device and managed to capture users' movements. Regarding the visualisation tool, it was possible for users to identify problems with the execution of their technique, especially concerning the direction of the force they applied to treat the walls of the canal. The simulator is expected to be capable of usage in preclinical and endodontic units to increase the students' practice time before having contact with real patients.

8 Acknowledgements

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References

[1] Ingle, J. I., Bakland, L. K., & Baumgartner, J. C. (Eds.). (2008). Ingle's endodontics 6. PMPH-USA.

[2] Marras, I., Nikolaidis, N., Mikrogeorgis, G., Lyroudia, K., & Pitas, I. (2008). A virtual system for cavity preparation in endodontics. Journal of dental education, 72(4), 494-502.

[3] Liu, G., Zhang, Y., Townsend, W. Force Modelling for Tooth Preparation in Dental Training System. Virtual Reality Journal, Springer 12(3). 125-136. 2008.

[4] Suebnukarn, S., Hataidechadusadee, R., Suwannasri, N., Suprasert, N., Rhienmora, P., & Haddawy, P. (2011). Access cavity preparation training using haptic virtual reality and microcomputed tomography tooth models. International endodontic journal, 44(11), 983-989.

[5] Luciano, C., Banerjee, P., DeFanti, T.: Haptics-based virtual reality periodontal training simulator. Virtual Reality Journal, Springer. 13(2), 69-85. 2009.

[6] Wang, D., Zhang, Y., Hou, J., Wang, Y., Lv, P., Chen, Y., Zhao, H. iDental: a haptic-based dental simulator and its preliminary user evaluation. IEEE Transactions on Haptics. 5(4), 332-343. 2012.

[7] Tsao, C. C., Lin, F. Y., Liou, J. W., Wen, P. H., Peng, C. C., & Liu, T. S. (2013). Force Sensor Design and Measurement for Endodontic Therapy. Sensors Journal, IEEE, 13(7), 2636-2642.

[8] Li, M., Liu, Y. H. (2006, May). Haptic modeling and experimental validation for interactive endodontic simulation. In Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on (pp. 3292-3297). IEEE.

[9] Bogoni, T. N.; Pinho, M. S. Haptic Technique for Simulating Multiple Density Materials and Material Removal. In: 21st WSCG 2013, Plzen, Czech Republic, June 24-27, 2013. p. 151-160.

[10] Zilles, C. B.; Salisbury, J. K. A constraint-based god-object method for haptic display. Intelligent Robots and Systems 95.'Human Robot Interaction and Cooperative Robots', Proceedings. v. 3, p.146–151, 1995.

[11] Ho, C-H, Basdogan, C.; Srinivasan, M.A. "Efficient point-based rendering techniques for haptic display of virtual objects." Presence 8.5 (1999): 477-491.