# A Tooth Drill Haptic Simulator of Virtual Reality

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**Abstract**

Dental medicine is a very practical and technical discipline that consequently requires the dedication of a high number of hours dedicated to training. When the training phase starts in the preclinical environment, students are highly dependent on feedback provided by teachers. Combining the fact that there is an increasing number of students choosing to study dental medicine, consequently, the time that each teacher can spend to accompany each student is highly affected. Preclinical training focuses primarily on the use of typodont. This teaching methodology is low cost, manages to offer some realism, but the exercises are always performed on teeth that do not allow to distinguish the different layers. Additionally, the execution of the procedure is irreversible, and it's hard to receive feedback from a professional while preparing a cavity.

The work proposed in this document focuses on the development of a haptic simulator of virtual reality with focus on the instrumentation phase.

Therefore, this work intends to study the adaptation of virtual simulators, while using haptic feedback and virtual reality technologies in a teaching environment, to co-exist with the traditional training method, using typodont.

**Keywords:** Simulation, Haptic Feedback, Virtual Reality, Tooth Drilling

## 1. Introduction

The technology in the recent decades has evolved dramatically and consequently this technological revolution as also reflected in the world of dental medicine. Dental medicine is a very practical discipline and the predominant teaching methodology during the training phase in a preclinical environment mostly uses typodont phantom heads and typodont teeth. However, these traditional techniques have undergone few relevant changes over time. The development of virtual simulators for preclinical training begins to present the possibility that these can become a valid and accessible training tools for students in a preclinical environment. Such progress represents the possibility of expanding the traditional teaching methodology practiced in the field of dentistry.

Virtual reality technology in conjunction with haptic devices has the potential to be used in a preclinical training phase, in order to provide the student with a training session in an immersive simulation environment. This is achieved through the immersive capabilities provided by the virtual reality hardware that are capable of deceiving the brain. This ability is a very strong and important factor in the world of simulations. The simulators are great training tools, so they allow a participant to carry out countless training sessions, in addition all training sessions are performed in a perfectly safe virtual environment. The simulators have the advantage of allowing the exposure of the student's to different scenarios, thus contributing to the acquisition of new skills, also allowing the student to have contact with different situations and another positive factor of the simulators is to allow contact with scenarios that can be difficult to replicate or find in the real world.

Virtual reality is an immersive technology and for this it implies that the user's senses are deceived, thus transmitting the feeling that the user is actually in a different world. In order to achieve the immersive effect it is necessary to resort to a virtual reality interface, which materializes in the use of a head-mounted display, HMD, that is, the virtual reality oculus. The possibility of interacting with virtual objects through commands, or using the hands or even using haptic devices, makes the experiences more immersive and realistic.

In addition to virtual reality technology, augmented reality technology is also widely used in the implementation of simulators in dental medicine [17]. This technology allows combining elements from the real world with elements from the virtual world, where the idea is to add a digital layer on top of the real physical environment, in this way reality is complemented with information generated in the virtual environment.

However, augmented reality technology as opposed to virtual reality needs the real physical world to be able to provide a user experience. This type of technology, although valid, does not meet the requirements of the simulator's vision, since it aims to provide the student with an immersive experience without needing to resort to any usual training tool. The solution presented in this document aims to provide the student with a different and more realistic experience compared to the conventional training format, which is composed of phantom heads and typodont. Using an augmented reality system, the simulator would have to depend on real phantom heads or typodont, to be able to carry out the simulation and add value over the real world.

Haptic technology is one of the key elements for students to use and adopt virtual haptic simulators, given that this type of technology enhances the immersiveness and realism of the experience provided by simulators [14]. Haptic devices allow the user to interact with the virtual world using tactile feedback. The feedback transmitted to the touch haptic device is derived from the applied force from the user as well as from the movement on the x, y and z axis [20]. The haptic simulators in the medical field contain a haptic device that allows the user to conduct training sessions on virtual models of teeth or dental arcade, and the models can be completed with the various soft tissues in order to create a more realistic simulation.

The interaction of the user with a stylus, haptic pen, must be very similar to the manipulation of a real device, in this case the turbine, since this device aims to simulate the functionalities of a real turbine. There are, however, some studies that in order to increase the realism of the experience, modify the haptic device to support the real instrument at the tip of the haptic pen. In this type of simulators, the most common function of haptic devices is to simulate the use of cutting instruments, thus allowing the user to feel the various resistances offered by the different materials that make up the tooth [13, 20]. The haptic pen can also be used to simulate mirrors, as well as carpule syringes.

## 2. Background

2.1. Introduction of Simulation in Dental Medicine
Dentists perform complex procedures that require a perfect technique, where an error can have serious consequences. For these to reach a good level of quality, it is necessary to spend many hours training. Since the foundation of the first dental school, there has been a need to train students through simulation [14]. The first training sessions carried out in schools used extracted teeth, and this training technique presented difficulties in training sessions since this is a scarce resource. The preparation of students through simulation techniques was considered important from an early age because the procedures are irreversible, which demonstrates the need to invest in preclinical training, because ill-prepared professionals put the health and well-being of patients at risk [14]. The first simulator developed was quite simple and became universally accepted by the dental medicine community. The phantom, named by Phantom Head, was the first dental simulator, created by Oswald Fergus in 1894, consisting of two jaws, composed of extruded teeth, secured to a metal bar in order to simulate a patient's mouth [14].

The modern version of a phantom head is made up of plastic and or resin teeth, containing the shape of the head in order to simulate a patient, the phantom head is positioned as if it were a patient, allowing the student to train his body and hand posture during training. These are some advantages of phantom heads and the typodont, that represent mostly the only training tools available to students undergoing preclinical training.

According to the investigation carried out by Perry et al. [14] and taking into account the observations of professionals, the teaching methodologies in dental medicine have not undergone relevant changes, except for some universities that have already started integrating simulators [12] in the preclinical training phase.

The teaching methodology in relation to training is divided into two phases. After the student acquires theoretical knowledge about the anatomy of the tooth and the dental arch, the professionals provide theoretical schematic representations of the procedures, consequently the students have to replicate these procedures in plastic models, such as phantom heads or typodont, figure 1. In the later phase, students apply the procedures in the clinical setting on real patients under the supervision of supervisors [11].

The introduction of phantoms made it possible to repeat the simulation of theoretical clinical conditions after verbal and visual instructions on execution. Phantoms are universally accepted due to the approximation of reality that they manage to transmit due to their low cost. The phantom training allows the student to train their posture during the procedure, allows the real instruments to be handled, allows the tasks to be repeated, makes it possible to position the phantom heads as if it were a patient, allows practicing dexterity with the mirror and cutting instruments, when using the mirror during training, it allows training indirect vision and also allows the student to exercise the finger rest technique, which is a necessary technique that

(a) Typodont dental arch with support for the teeth.

(b) Typodont in plaster block.

Figure 1: Typodont

students acquire at an early stage because it provides stability in handling the instruments.

However, phantom heads do not allow training sessions based on cases of real patients, students are limited in view of the training situations that phantom heads or typodont are able to provide, it is necessary an expensive infrastructure assembled for students to be able to use the turbines, students at an early stage are very dependent on a tutor to provide feedback and sometimes that feedback is not very objective [18].

2.2. State of Simulation in Dental Medicine

The training of tactile skills is something very important in the world of dental medicine, but on the other hand requires a teacher to spend many hours of tutoring with students, often in personalized accompaniment, which consequently ends up consuming too much time for teachers. Such difficulty is due to the fact that the student cannot feel what the teacher feels nor can he transmit it, as well as the teacher cannot physically guide the student because he does not feel the resistance of the tissues.

To overcome these limitations Kolesnikov et al. [12] carried out a study that resulted in the development of a virtual reality simulator in the field of periodontics with the aim of helping students in obtaining sensory motor skills in dentistry. According to Kolesnikov et al. haptic feedback consists of a professional performing a certain procedure and the simulator recording the procedure, to be used in training sessions later. During the recording phase of the procedure, the simulator collects the force exerted on the tissues, as well as the position of the instruments over time, thus allowing to reconstruct the trajectory of the instruments. The recordings are stored in the system for later use by the students in training sessions, so the student has access to the way a professional performs the diagnosis and performs the procedure. During the student's training phase, the tutor does not need to be monitoring the exercise [12].

The end user of most dental medicine simulators is the student, so Bkr et al. [7] conducted a study with 4th and 5th year dental students using the Simodont simulator [6], to determine what students think about this type of simulator.

The 4th year students were more excited to try this type of solution compared to the 5th year students. However, after the experience, the 5th year students evaluated most aspects in a more positive way than the 4th year students. Such an event is due to the fact that the simulator does not meet the high expectations of 4th grade students. [7].

Although they only use the simulator in a single session, the 5th grade students felt more comfortable using the system, leading to the conclusion that the 5th grade students have more experience and more dexterity. For 4th year students not adapting very well to the system, it might indicate that it may not be accessible to students who have not yet acquired a certain level of experience. However, the students recognized the potential of the system in preclinical training, but nevertheless, they stressed that the simulator feedback must be complemented by the feedback of a professional, so they do not want to be taught only through machines.

The study by Rhienmora et al. [17] culminated in the development of a virtual haptic simulator in two phases. In the initial phase, the simulator was developed using virtual reality technology and then expanded to support augmented reality. The purpose of using augmented reality is due to the fact that they came to the conclusion that they could allow the user to perform the training in a correct posture. An expert evaluated the system, concluding that the implemented techniques are able to bring the training environment closer to the real clinical environment, due in part to how the handling of the instruments is performed.

Gat et Al. [8] conducted a study on the IDEA Dental simulator, to determine the potential of this simulator as a teaching tool without the assistance of a professional, as well as the usefulness of the tasks to be performed. IDEA Dental is a haptic virtual reality simulator that uses gamification techniques. To train manual dexterity, which is the focus of the simulator, the student performs several exercises that are divided by levels, in the interface the percentage of tissue that needs to be removed using the turbine is shown. The exercises in this simulator only focus on training manual dexterity and according to the evaluation, this type of isolated exercises are useful to carry out an individual learning of manual dexterity.

In the area of implantology, the procedures are traumatic for patients, and they present a risk due to the anatomical complexity of operations in the maxillofacial region, as well as the high cost of materials. To mitigate such difficulties, it is usual to resort to computer-aided technologies to simulate the procedure [9, 15] or to help in planning the process. The Dental Implant Surgery Simulator [9] solution allows you to reconstruct patient models based on CT scans. Simulation based on data from real patients allows to identify problems that may occur during implant surgery and to identify a solution. This study allows us to identify which drill diameter and turbine speed is ideal for a given case.

This type of solutions allows to significantly reduce the cost of experiments on cadavers, and such experiments do not comply with ethical standards. Training with parts of cadavers or animal bones is widely used in training, however the materials are of low quality and the experience they offer is quite different from reality. There is a failure in training in such a way that professionals are already exerting the profession when they resort to this training method, the other possibility being practice through real cases. In other words, there is a gap in the development and accessibility of simulators in teaching for the placement of implants in a preclinical phase. The SimImplanto [15] simulator focuses on a single step of implant placement, in the drilling procedure prior to placing the dental implant in the dental arch using a haptic interface. The simulator allows modulation based on a plaster model of a real patient, after which the plaster mold is scanned using the Next Engine 3D Scanner.

There are several commercial solutions, such as Kobra Simulator [1], Leonardo Training Simulator [2], , Moog Simodont Dental Trainer [3], Virteasy [4], Voxel-Man [5]. These types of simulators follow the development approach in a bench format, so the price for a simulator/bench can vary between 20,000 $ and 80,000 $. Some of these simulators have already demonstrated their value as a training tool that are already accessible for preclinical training at certain universities.

## 3. Implementation

The solution, Dentify consists of a haptic virtual reality simulator with a focus on the instrumentation phase. The solution consists of three main modules, the simulation controller, the haptic interface and the virtual reality module. It was developed on the Unity3D game engine, using the C# programming language. One of the simulator's interfaces with the user is through the rendering module of all visual and virtual content, being achieved through the virtual reality headset, Oculus Quest. To integrate the virtual reality with the simulator, we used the plugin supported by Unity, XR Interaction Toolkit.

Being the focus of the simulator in the cavity preparation phase, it is necessary to provide an interface with the user capable of simulating the actions performed by the user on a real dental drill. Thus, the simulator integrates a haptic device, the Touch Haptic Device developed by 3D Systems. This device has the ability to simulate the same range of motion performed by a specialist when handling a dental drill, it also allows the configuration of the resistance offered when moving it around, as well as the level of vibration. The process of integrating the haptic pen with the simulator used the 3D Systems Openhaptics® Unity Plugin [21] plugin, developed and maintained by 3D Systems.

The implemented solution was achieved with a total cost of hardware, within the 4 digits, below €2,000, that is with the virtual reality headset and the haptic device.

The figure 2, allows to identify the three most important modules of the system. The simulation module is responsible for controlling the entire simulation, being composed of several sub-modules, such as exercise configuration, deformation, feedback and statistics.

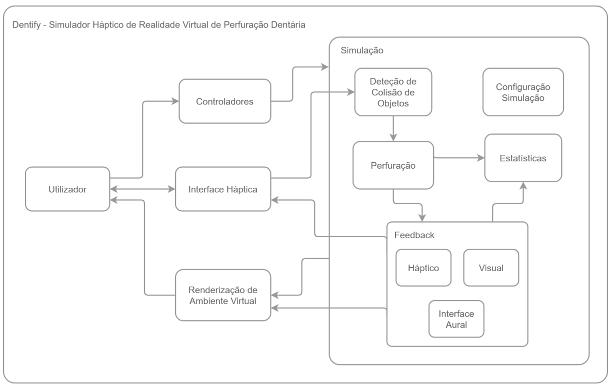



Figure 2: Dentify Simulator Architecture

The simulation takes place in a virtual environment and is complemented with the haptic device and the virtual reality headset and the corresponding controllers. The virtual environment consists of three scenarios. The first scenario only allows the user to set the username, so when finishing a simulation exercise, the statistics of the performed exercise are exported to a file in JSON format and organized in a folder with the username, containing statistics from previous exercises. This scenario does not use virtual reality and to proceed in the simulation, it's necessary to use the mouse.

When progressing in the simulation, the user is introduced to a new scenario, where he has the possibility to configure the simulation environment. The user has the possibility to choose the number of teeth, which type of cavity to prepare, choosing from preparing a class 1 or class 2 cavity with the respective guide limits. It's also possible to set the dominant hand, which is the hand handling the dental drill, as well as whether the exercise is to be performed in training mode or evaluation mode.

Starting the simulation, a timer is simultaneously started which is responsible for determining the duration of the simulation. When starting, the user can immediately see part of the dental drill, the tooth to be deformed, a replica of the tooth to be deformed, but with all layers in translucent mode, which aims to be able to serve as a guide, allowing to see which and where are the internal layers that make up the tooth, figure 3. On the left side of the user, a panel is presented that allows to carry out various actions within the simulation, such as hiding or showing the different layers of the tooth, such as enamel, dentin, pulp and gum, it is also possible to switch between two types of spherical drills, differing only in their diameter, additionally it is possible to make the dental drill translucent and disable the vibration provided by the haptic device.

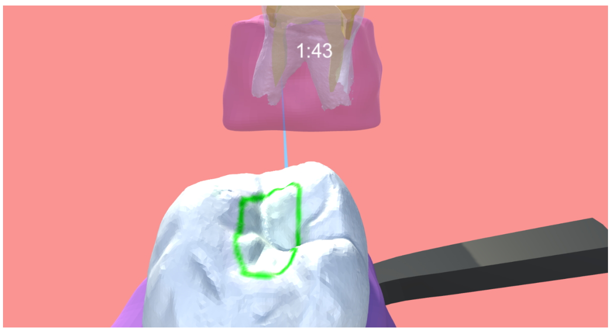
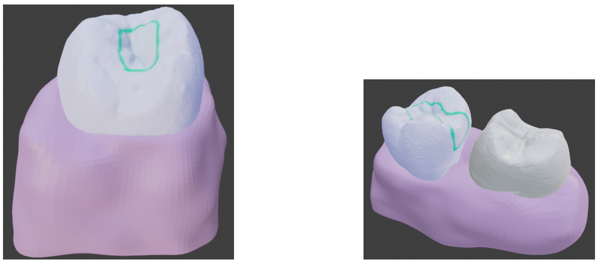



Figure 3: Simulator Initial View

The presented solution, supports up to 4 cases of training sessions. It is possible to prepare a class 1 and class 2 cavity, the remaining cases are variants. The supported variants allow adding a tooth adjacent to the tooth to be deformed. The cases presented by the simulator are based on real teeth, as well as the limits presented. The assistance of a specialist in the field of dentistry was essential in order to obtain a tooth and its cavity limits in a digital format. After the tooth was selected and cleaned, an intraoral scan was performed by the professional before any cavity preparation was performed, thus obtaining a virtual model of the tooth to be instrumented. The specialist then prepared a class 1 cavity followed by a class 2 cavity. Overlapping the scanned models, without cavity and with cavities, it was possible to obtain the limits of the preparation of the class 1 and class 2 cavity. Thus, each exercise supported by the simulator consists of preparing a cavity based on the limits prepared by a specialist in the field of dentistry.



(a) Exercice to prepare a class 1 cavity

(b) Exercice to prepare a class 2 cavity with an adjacent tooth

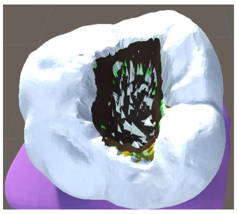
Figure 4: Two types of exercises supported with the location of the respective limits marked in green

To perform the deformation of the models, described in figure 4, the Impact Deformable [16] plugin was used, which focuses especially on this type of deformation, with active development and maintained for several years. Modifications were made to this plugin to update the colliders only when there is no deformation in order not to interfere with the experience, since updating the colliders as soon as the deformation happens, it sometimes caused performance problems. However, this change does not interfere with the visual deformation process, the user can observe the wear as soon as it starts, as expected, just like in real life.

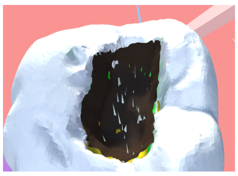
To perform the deformation, the simulator emits a ray, raycast, in the direction of the drill, thus being able to determine the level of proximity to the detected layers, advancing only to the deformation process if the drill is at a minimum distance from the closest layer. The dental drill only wears out at its end because, as it needs to perform the deformation at a certain point, the raycast technique is used for this, and the plugin does not support deformation based on a model format.

Additionally, in order to be able to wear on dental tissue it is necessary to have a configuration. All tissues that are deformable, enamel, dentin, pulp and gum, require to have associated a script that is responsible for performing the deformation, Impact Deformable Remake. As shown in the previous figures, it is possible to associate a resistance to each tissue, the deformation radius, as well as the speed with which the wear must occur in the different axes, x, y and z. The deformation area depends on these three variables. The current solution supports the wear carried out by spherical drills, and other types of drills would require manipulating the configurable values available or may require modifications to the deformation effect itself, to adapt to the shape of the respective drill.

Although this method allows to perform a simulation of the deformation in the dental tissues realistically, this technique has some limitations. The deformation process occurs only at the vertices level, and it is possible to move the vertices in such a way that walls are created, which are represented by large areas. This phenomenon happens because when performing a great deformation in a certain area the vertices will move significantly downwards, with the adjacent vertices continuing at the top of the surface, therefore the dimension of the edges will increase considerably and as the edges are not deformable, tissue walls are formed, which, although they appear to be deformed, are not directly deformed. In order to deform these walls, it is necessary to deform the adjacent vertices that are at the top of the surface and so on until the end of the model is reached. Figure 5(a) shows a cavity full of enamel walls, which were not proper deformed. Increasing the size of the deformation and not rushing through the deformation process results in a cavity with less enamel walls, as presented in figure 5(b).



(a) Cavity 1 prepared resulting in a high number of enamel peaks



(b) Cavity 1 prepared with a significantly reduced number of enamel peaks

Figure 5: Results of the preparation of class 1 cavities

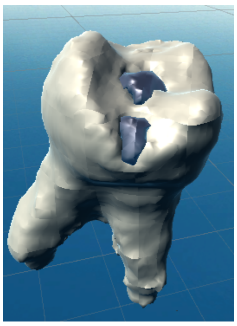
During the deformation process, the interface that replicates the behavior of a dental drill provides haptic feedback and this is transmitted to the user's hand, exactly as if he were handling a real dental drill. The haptic device offers resistance and vibration, being two aspects very present and important in the cavity preparation phase, since the dental drill being a high speed rotary instrument offers some level of vibration and the dental tissues to deform offer different levels of resistance. The haptic feedback allows the user to feel different resistances depending on the area to be deformed, with the haptic pen activating the appropriate resistance as soon as the deformation in a certain area is initiated.

### 3.1. Voxel Experiment

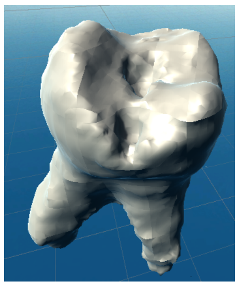
The deformation process described above has some limitations. In order to try to mitigate these problems, as they proved difficult to solve in the solution presented, due to the implementation details, there was a brief exploration of a different model generation technique. The technique uses voxels, blocks, to generate the models. Using this technique the models are built programmatically, thus managing to create a model that has blocks throughout its interior, thus there are no empty spaces. The more blocks used, the more detail the model presents. The Voxel Generator [10] plugin was used to support the engine responsible for generating models and deforming the respective blocks.

In this way, the simulation process becomes more realistic, since the preparation of cavities based on well-defined limits takes place only in a preclinical environment, in contrast, in the clinical environment, there is the removal of only the caries tissue.

Using this technique the tooth model, figure 6, is composed of several small convex blocks, the deformation process becomes simpler, and it is possible to use native methods in Unity to detect collisions, since the models used are always convex. Thus, whenever there is contact with the bit in the blocks it is possible to remove only the blocks in which there was contact with the dental drill, and the smaller and greater the number of blocks that make up the model, the smoother the wear will be.



(a) Tooth composed of caries tissue on two sides.



(b) Tooth after caries removal.

Figure 6: Removal of caries from tooth

## 4. Results

The developed solution focuses on a technical phase within the dental medicine, which is the instrumentation phase and since being the main task, the validation of the simulator needs to be carried out by specialists in the field of dental medicine.

Professors and doctors, active in the clinic environment, make up the group of experts considered for the evaluation phase. For the study, all participants who were able to exert the activity professionally were then considered able to evaluate the simulator. The study consisted in two distinct evaluation phases and in each of the evaluation sessions tests were carried out on different versions of the simulator. The last evaluation phase was carried out using the final version of the solution. However, in the first evaluation phase, there was an exception in the group of participants. Two 5th grade students took part in the testing phase, in order to get more feedback on the first version of the simulator. The feedback returned by the students was considered valid since they are only a few months away from being able to exert professionally. The evaluation phase was carried out mainly with professors and doctors, due to the reduced time to subsequently carry out a new study with a group composed only of students. Since it only makes sense to carry out tests with the participation of students when the technical capabilities of the solution were validated by specialists in the field.

With the study carried out, it was intended to be able to draw conclusions, based on feedback from specialists in the field of dentistry, on the contribution of the current solution and the possibility of adopting this type of simulators in the preclinical environment, using virtual reality and haptic feedback technologies, as a complement to traditional preclinical training techniques.

Both evaluation phases followed a set of well-defined steps, described in a guide. Each evaluation session took an average of 1 hour and the execution of the simulator evaluation exercise took an average of 10 to 15 minutes.

Each evaluation session began with a participant filling out a consent form and demographic profile form. Then, the evaluation moved to the project's presentation phase, by describing the project, what its objectives were, what kind of exercise would be performed, followed by an explanation of the devices that make up the system and how to use them. In the next stage, the participant had the opportunity experiment and get familiar with the simulator, before executing the intended exercise. After executing the exercise, the participant answered several questionnaires, such as questionnaires regarding the virtual reality experience, usability, workload, experience with the simulator, and finally the feedback collection process ended with an interview with the participant regarding their experience with the simulator.

The last evaluation phase consisted of 13 participants. All participants are trained and actively exerting in the field of dentistry. Two of the participants in this evaluation session participated in the first evaluation phase. All participants have a master's degree in dentistry. The vast majority of specialists are, at the time of the tests, exerting the areas of dentistry and oral rehabilitation. However, professionals in the fields of implantology, orthodontics and surgery were also part of the study.

The average experience of specialists, translated into years in a clinical setting, is approximately three and a half years. The minimum reported time exerting as a dentist was one month and the maximum was 14 years. Nobody reported frequent contact with virtual reality or haptic feedback type of technology.

**Exercise Plan and respective Number of Participants**

- 6 participants - Class 1 Cavity Preparation - Training Mode
- 3 participants - Class 1 Cavity Preparation with Adjacent Tooth - Training Mode
- 2 participants - Class 2 Cavity Preparation with adjacent tooth - Training Mode
- 2 participants - Class 1 Cavity Preparation - Evaluation Mode

### 4.1. Virtual Reality Experience

Some participants reported difficulty maintaining focus, headache, blurred vision and tired eyes. Most participants who reported these effects wear glasses on a daily basis. Therefore, the use of glasses may be the cause of these effects.

At the beginning of all simulation exercises, an explanation was provided and the participant was assisted in the process of putting on and adjusting the VR headset, so they would be properly adjusted to them and be able to observe the virtual world well, without blurring. A factor that is at the origin of the blurred vision and difficulty in maintaining focus is the use of a mask. The mask was necessary due to the pandemic times, sometimes the vapor coming from the breath escaped through the upper part of the mask whereas a consequence it fogged the lenses, thus restricting the field of vision and affecting the experience.

Thus, it was possible to conclude that the virtual experience provided by virtual reality glasses can provide some side effects, the most frequent being tired eyes, headache and blurred vision, being the tired eyes the most frequent, with a maximum of 3 out of 13 participants to report the effect. All these effects were felt by only a small part of the participants and always in a light way.

### 4.2. Usability

The score ranges from 1-100 and 68 points is considered the average score of the systems, according to a wide evaluation on different systems [19].

Figure 7 shows the results of the usability questionnaires. The highest reported result was 90 points and the lowest 62.5 points. Based on the expert's feedback, the average usability score of the system is 77.5 points. Thus, there was a slight increase of 3.75 points, compared to the results of the first version of the simulator. This gives a score almost 10 points above the average of 68 points, meaning the users find the system easy to use and understand, although existing a slight learning curve.

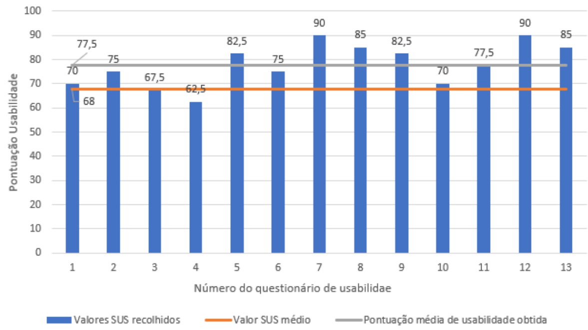



Figure 7: System Usability Scale (SUS) Scores

In this phase, the reported values are more cohesive, with a standard deviation of 8.4 points, where in the first phase it was 12.1 points. The expert's opinion also proved to be more cohesive, so the value of the standard deviation decreased about 4 points, where in the first phase a deviation of 12.1 points was obtained.

To obtain a good score in this questionnaire, according to the questionnaire structure, the odd questions must get an answer close to the value 5 (I totally agree) and the even questions must get an answer close to the value 1 (I totally disagree). According to the results, this was the trend followed by the participants, in any of the phases, except for question 4 (I think I would need help from a person with technical knowledge to use the system.).

### 4.3. Work Load

The average workload dropped to 33%, compared to the 38% resulting from the first evaluation session. Therefore, the changes made in the simulator between evaluations contributed to a lower perception of the workload. The standard deviation of the presented values of the workload is 14.7%, which suggests that there is some disagreement in the results, however it is not at an extreme level. There was one participant who had a very high perception of the workload, 77% out of 100 %. Comparing with the reported minimum value of 20% there is a considerable discrepancy between the lowest value and the maximum reported. The high workload result of 77%, is directly related to the limitations of the simulator, however there were participants who managed to adapt better to the simulator and its limitations, providing to be more tolerant to experimental prototypes.

According to figure 8, it is possible to detect that some high values have been reported for the different factors evaluated, such as the level of mental and physical effort, also a high value in the performance and frustration. At the level of mental effort, it was identified that it is due to the high number of functionalities supported by the VR controller and the effort to memorize them. The physical effort is due to the lack of a finger rest spot to provide stability and control to the manipulation of the haptic device and thus mitigating the tiredness felt by the lack of supports. There was a division in the opinion of experts on whether the time taken in the simulation corresponded to reality. It was reported a slight level of frustration due to the lack of finger rest and the deformation not happening exactly how and where the specialist intended to.

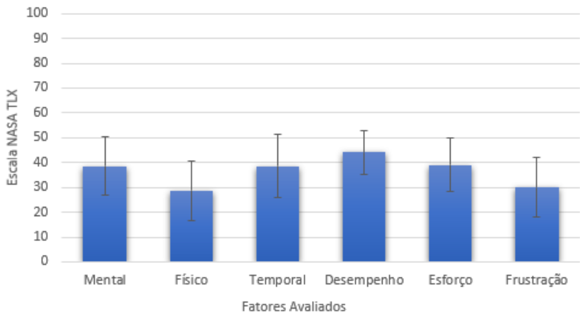



Figure 8: Average NASA TLX values considered

### 4.4. Feedback of the Experience

According to the experts, the factors that limit the simulator are the lack of finger rest spot and the deformation occurring only at the end of the drill. All experts adhered well to the experience, meaning that resorting to virtual reality can help increase students curiosity and interest, as well as serve as a tool for exploring and acquiring new skills.

That said, all the participants considered adopting this type of technology as a complement to the traditional training techniques, however the current prototype would need to resolve the limitations already identified by the professionals to be ready to be used by any student. According to the opinion of dental specialists, using the simulator as is to carry out this type of technical exercise as a training tool by students may incur in the adoption of an incorrect hand posture, thus making it difficult to acquire ideal postures.

## 5. Conclusions

The work presented describes Dentify, a tooth drill haptic simulator of virtual reality. The implementation details of the work were described in the chapter 3, followed by their evaluation in chapter 4. The work here described resulted in the implementation of a functional prototype, although with some limitations.

Thus, based on the results obtained, it is possible to conclude that the solution has the potential to be adopted as a complement to traditional training techniques in a preclinical environment. It was determined that professionals are interested in updating the range of training tools available to students, in order to make the students more interested and to be able to acquire skills more quickly.

The consensus of the experts is that the simulator and these types of solutions, using virtual reality technologies and haptic feedback, have a high potential in the training phase of students. There has been an interest in making this simulator available to students. However, although the results are positive, and show promise, the experts only considered incorporating this simulator if the relevant limitations identified were resolved, because some current limitations can cause negative effects on student learning, such as the working position with the turbine, because the simulator transmits greater ease of wear when the position of the haptic tool is completely vertical, where this is not the case in the real world.

In conclusion, the study managed to obtain positive results regarding the adoption of this type of simulators and related technologies.

### 5.1. Future Work

This section aims to present the possible next steps in order to make the solution more complete and provide an experience closer to reality. The suggestions presented are based on the known technical limitations of the simulator as well as the feedback provided by the various specialists in the field of dental medicine.

**Finger Support** Referred by several experts, the finger support is essential in the cavity preparation process, and they use this type of support to obtain more stability and control when handling rotary instruments. Consequently, this support is reflected in a reduction of tiredness, together with the adoption of a comfortable posture and with flexed arms. So, it will be interesting to extend the 3D model of the turbine that is attached to the haptic pen in order to allow the finger support.

**Voxel Engine** Another very important factor in this type of simulator, which requires tissue deformation, is related to the composition of the different tissues to be deformed. The current solution, as presented, is composed of several layers, all of which are only composed of the visible surface, meaning all layers of the tooth do not contain any content inside, therefore, a simulation of the deformation action is carried out, being thus achieved through the manipulation of the vertices that make up the different layers.

In order to make the deformation process more realistic, that is, to be able to perform the deformation with the entire drill area, it is necessary to continue exploring a test case presented in the section 3.1, which is based on a voxel engine. The voxel engine is responsible for presenting the tooth and performing the tooth deformation process. This approach allows to solve the remaining factors that were considered to affect the experience the most, such as the deformation areas on the teeth are quite limited due to the turbine just wearing the tissue right at the extreme point of the model and the enamel peaks appearing during the deformation process.

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