Conference and Exhibition of the European Association of Virtual and Augmented Reality (2014)
G. Zachmann, J. Perret, and A. Amditis (Editors)

Development of a Haptic Training Simulation for the Administration of Dental Anaesthesia based upon Accurate Anatomical Data

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Abstract

In the dental curriculum, the initial administration of local anaesthesia injection on live patients is critical and students may experience a high degree of anxiety. Low self-confidence often caused by insufficient knowledge of anatomy has been repeatedly reported as one of the major causes. In this paper, we focus on the development of a haptic training system based upon an accurate anatomical model, which aims to encourage self-paced learning of the practical skills that are required in such procedures and to increase students' self-confidence. We first present the workflow we have considered to develop an accurate anatomical model of the human head and neck and introduce a Virtual Reality-based application commissioned by NHS Education for Scotland to support the learning of the anatomy in a safe and repeatable manner. Finally, we describe the functionalities of the haptic training system and discuss further developments with regard to existing research outcomes.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Virtual Reality—I.3.8 [Computer Graphics]: Applications—

1. Introduction

The understanding of mandibular anatomical structure and the ability to deliver correctly local anaesthetic techniques is a critical aspect of the dental curriculum [XLR13]. Dental academic institutions have considered different teaching strategies to improve both knowledge acquisition and practical skills in the administration of local anaesthesia techniques [BKB08]. Currently, EU dental schools, among them several from the UK [BKB08] [BTvdSB11], use a variety of materials including Information Technology (IT) solutions to support theoretical teaching of local anaesthesia procedures [MSA*08]. However, in most cases, the practical aspect of teaching is carried out on human subjects under the supervision of an oral and maxillofacial surgeon and/or a dentist [ROSJ09] [XLR13]. A minority of dental institutions have integrated pre-clinical dental injection practice procedures on non-human objects such as fruits, meat from dead animals (e.g. chicken legs) or physical workbenches supporting their teaching strategy [BKB08]. Despite the reports of many students who have been through a pre-clinical training procedure and who considered it a useful preparation before their first injection on a human patient [BTvdSB11], pre-clinical models usually lack objective and convincing methods of assessment of performance and lack tactile realism of human tissues [KÖMK10] [THB*10].

The initial administration of local anaesthetic injection on live patients remains difficult for dental students and tends to cause them a high degree of anxiety due to insufficient preparation [BKB08] [ROSJ09] [BTvdSB11]. The lack of knowledge of anatomy and eventual complications subsequent to the administration of anaesthetics [CP99] [ROSJ09] have been also frequently reported as a weakness of teaching strategies followed in some dental academic institutions [BTvdSB11].

The integration of IT solutions in current practical teaching strategies, and more specifically of Virtual Reality (VR) simulations enhanced with haptic force feedback, can support individual proactive, safe and repeatable learning leading to the reinforcement of practical skills, anatomical knowledge and self-confidence needed in the dental training curriculum for efficiently preparing dental students

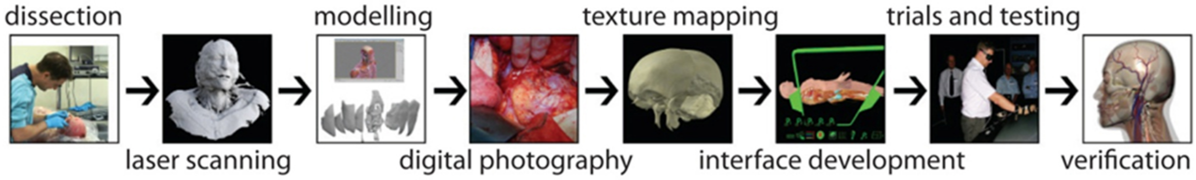

Figure 1: *Workflow for the development of accurate human head and neck interactive digital anatomy.*

for their first local anaesthetic injections on a live patient [BTvdSB11] [MAJ13].

This paper presents the development of a haptic-based VR training system which complements traditional training for the dental curriculum, aims to familiarize students with local anaesthetic techniques, such as the inferior alveolar and lingual nerve block anaesthesia, and encourage self-paced learning for mastering practical skills. The VR system allows practising the administration of local anaesthesia on an accurate representation of the human and neck anatomy [AMP14].

This work was commissioned by NHS Education for Scotland (NES) as part of a major project that aimed at the development of an interactive visualization application to support clinical teaching of human head and neck anatomy (http://www.nes.scot.nhs.uk/education-and-training/by-discipline/dentistry/about-dentistry/resources/3d-head-and-neck.aspx).

2. Virtual Reality and Haptics in Dental Training

The contribution of VR-based training as a complement to the physical training traditionally carried out for the development of practical skills in dental education has often been highlighted [QKMH03] [KÖMK10] [THB*10] [DAB*11] [XLR13]. VR-simulations provide, among other things, unlimited access to configurable training material and standardised skills assessment and performance feedback.

An important aspect of VR simulations to support the development of practical skills in dental education is the haptic interaction [TGS13]. The term "haptic" refers to the sense of touch. Haptic interfaces allow simulating realistic tactile sensations such as the elasticity (stiffness) and rigosity (friction) properties of human tissues that are crucial throughout dental procedures [LBD09] [KÖMK10]. Moreover, visual and haptic cues are considered to be complementary sources of sensory information in VR simulations [SBD*07].

During these last years, dedicated research efforts have been made to develop VR training platforms enhanced with haptic force feedback to improve the acquisition of practical skills in dental education, for review see [DAB*11] [SDCQ*12] [XLR13]. Some of these have been validated and are now part of the dental curriculum in many American and European colleges of dentistry [DAB*11] [GVB13] [XLR13].

The simulation of common clinical procedures involving needle insertion as biopsy and regional anaesthesia in virtual or mixed reality environments enhanced with haptics, has been widely studied [FHGH09] [UGR*10] [CJGC11] for review see [CMJ11]. However, only one study has emphasized the development of a VR simulation tool to support training of the needle insertion required for the administration of local anesthesia in dental surgery [CTN13] [CdSNT14].

Previous authors [CTN13] [CdSNT14] have presented the development and preliminary evaluation of haptic simulator that allows practising needle insertion for local anaesthesia injection in oral tissues. The anatomical model used for this purpose apparently consisted of a skull with only the gum tissue and mandibular muscles being displayed [CTN13]. They examined the design of their graphical interface but also that of the ergonomic attribute of the haptic device.Their results highlighted restrictions on the haptic device workspace and the traditional stylus handle suggesting a more syringe-like aspect would enhance the interaction within the virtual environment. Finally, their evaluation also suggested the accuracy of simulated forces.

3. Development of an Anatomical Model

The construction of a truly accurate anatomical digital 3D model of the human head and neck, to provide an interactive visualization experience required state-of-the-art data acquisition techniques combined with advanced real-time 3D modelling techniques. It was essential to base the model upon real medical data acquired from both cadaveric and live patients.

The development workflow was built upon data acquisition through 3D laser scanning, 2D data capture, data processing and optimisation, 3D reconstruction of objects and environments, photo-realistic rendering, user interface design and real-time interaction and display. Figure 1 shows the development workflow, which consisted of the identification of suitable donated cadavers, dissection, 3D laser scanning capturing surface measured data, 3D computer modelling of all structures, digital photography from surgical procedures, texture mapping, interface development to support user interactions in real-time, trials and testing. Verification and validation was conducted at every stage development with the final results being presented to a clinical advisory committee.

The model integrates different tissue types, the vascular system, and numerous structures that are suitable for both casual users and, in particular, those engaged in medical learning and teaching (Figure 2).

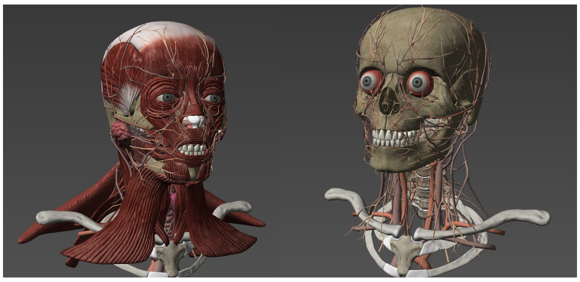

Figure 2: *Complete anatomical model (left) along with nerves and vascular system (right).*

A brain model based upon a volumetric dataset obtained from Magnetic Resonance Imaging (MRI) and Computer Tomography (CT) scans of the head of a live patient is currently under construction. Software platforms such as AMIRA (`http://www.vsg3d.com/amira/overview`) are used for image processing, segmentation and visualization of volumetric dataset.

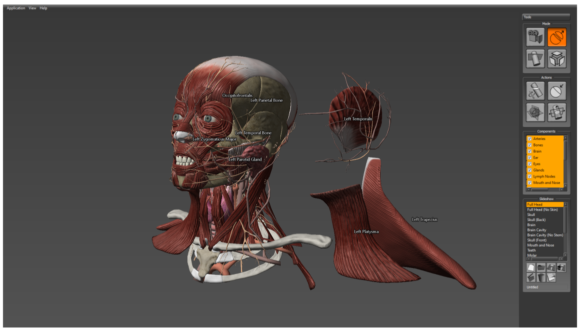

Figure 3: *User interface showing the drag-and-drop functionality allowing virtual dissection, and data labelling.*

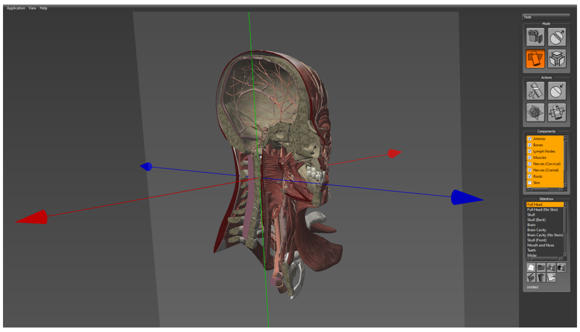

Figure 4: *User interface showing an orthographic view of the head and neck. As mentioned before, the brain model is currently under construction.*

4. Head and Neck - An Interactive and Real-time Application to Enhance Anatomy Learning

The Head and Neck Application consists of a simulation platform in which a digitalized anatomical model can be loaded. The platform was developed using OpenSceneGraph, an open source high performance 3D graphics toolkit (`http://www.openscenegraph.org/`). The primary focus of the application is to provide user real-time interaction with a validated anatomical digital dataset. The user can interact with the model through conventional input methods enabling data manipulation (translation and rotation) and navigation controls (zoom and pan). The user can also perform a virtual dissection by dragging and dropping, hiding or revealing relevant anatomical structures, and labeling data for instructional purposes (Figure 3). Virtual dissections can then be saved and reloaded.

Orthographic and oblique cross sections can also be performed to isolate specific information in planes similar to MRI and CT scans (Figure 4).

The accompanying suite of manipulation and navigation tools allows enhancing the interaction using an Xbox game controller and motion capture technology for tracking the user's point of view. Together with active or passive stereoscopic projection, it provides an immersive experience for users to fully explore and investigate head and neck anatomy beyond a one-to-one scale.

5. Haptic Dental Injection Simulation

The Haptic Dental Injection Simulation consists of a VR training system which is used so far as a familiarization instrument for the administration of local anaesthesia in the surroundings of the inferior alveolar and lingual nerves located on both sides of the mandible. The system means to complement the practical training traditionally provided in dental training, aiming to encourage self-paced learning and thus reinforcing students self-confidence during the performance of their first injections on live patients.

The system displays the head of a virtual patient with an open mouth and the virtual hand representing the dental student's hand stretching the patient's cheek (Figure 5). As with the anatomical model displayed by the Head and Neck Application, manipulation of the virtual patient head and navigation in the virtual environment are supported by conventional input methods. The interaction technique to carry out the administration of local anaesthesia is ensured by a haptic force feedback interface. A Geomagic Touch (formerly known as Phantom Omni) (http://www.geomagic.com) is used to control in position and orientation, a dental syringe in the virtual environment. This device consists of a punctual inter-actuator able to sense position and orientation on 6 Degrees Of Freedom (DOF) input and render forces up to 3.3 N onto 3 DOF output at 1 KHz within a delimited workspace (up to 160 W x 120 H x 70 D mm). The haptic interface enables simulating haptic sensations traditionally perceived when the tip of the needle makes contact with soft tissues, teeth and bones. Moreover, the haptic device simulates the needle insertion using a concept similar to that of a puncture presented in previous works [KNP11], adding haptic sensations (tissue density) corresponding to the different layers of tissue being penetrated, along a constraint line originated at the insertion point. The system can be configured to provide training on both sides of the patient's mandible.

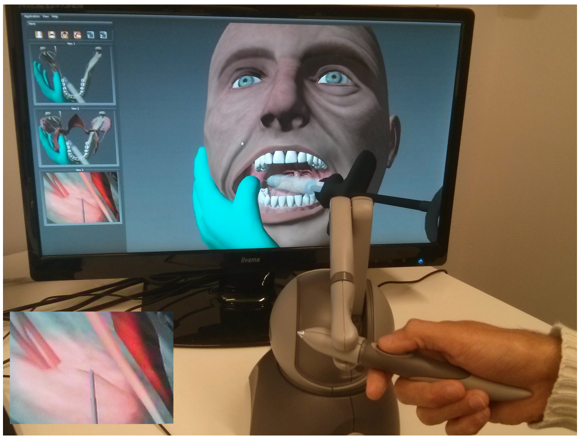

Figure 5: *Injection of local anaesthesia in the right side of the virtual patient*

To carry out the injection of local anaesthetic into the region of the inferior alveolar nerve, the virtual needle must be slowly inserted into the soft tissue surrounding the mandible. Once the tip of the virtual needle has reached the area surrounding the nerve, the student can proceed to the injection of local anaesthesia by pressing button 1 of the haptic device. As a result, the syringe plunger is pressed down and the anaesthetised area gradually turns red indicating the region has been numbed (Figure 5). The procedure can be reset and the injection graphical outcomes removed by pressing the button 2 of the haptic device, and thus rehearsed repeatedly.

The estimated times for the injected area to be numbed and the elasticity of the simulated tissues have been determined heuristically by a committee of dental experts.

Along with realistic haptic sensations, the system also reproduces auditory cues simulating the virtual patient giving warning when the procedure becomes painful, such as a sensitive area or a nerve has been reached by the tip of the needle. Additionally, augmented information feedback in the form of textual contents can be prompted to inform dental students about the cause of the pain.

Moreover, the system can be enhanced with the provision of augmented information in the form of three points of view that could not be obtained throughout the training traditionally conducted in the real world. Additional points of view are provided in a side panel located on the left side of the monitor (Figure 5): (1) The top view shows the mandible with the inferior alveolar and lingual nerves, which are relevant in this procedure; (2) The middle view shows a similar viewpoint but includes other relevant structures (parotid glands, buccinator, the superior pharyngeal constrictor and the medial pterygoid); (3) The bottom view consists of a close-up on the tip of the needle. According to behavioral psychologists, such aids may be beneficial at the early stages in the development of practical skills, however they have to be removed when the student achieves proficiency [Sch08].

In addition, the system allows for simplifying the simulation by removing selectively less relevant anatomical parts from the training environment (Figure 6)

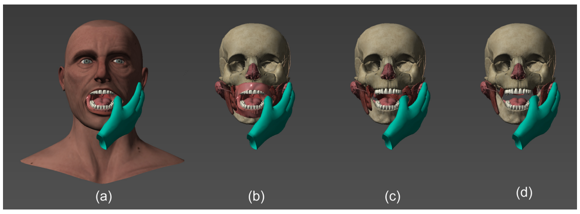

Figure 6: *Virtual environment displaying: (a) the complete anatomical model, (b) the mandibular structure with mucosa , (c) the mandibular structures, and (d) the mandibular structures, excluding buccinator and superior pharyngeal constrictor muscles*

6. Conclusion and Future Works

In this paper, we have presented the workflow for the development of an accurate anatomical model, used in an interactive virtual environment for enhancing the learning of the human head and neck anatomy. Using accurate anatomical data, we have also developed a VR training system for dental anaesthesia injection enhanced with haptic force feedback. Our training system is currently used by several dental colleges in Scotland as a familiarization instrument, aiming (1) to reduce the degree of anxiety typically experienced during initial injection procedures on live patients, (2) to encourage self-paced learning within a safe and repeatable environment and (3) to provide coherent clinical decision-making through consistent computer-aided assessment.

Our training system fills a gap in the market, as it currently the only system based upon highly accurate anatomical data specific to that purpose. However, as mentioned in a concurrent study [CdSNT14], formal assessment of our system in order to validate the training effect is still pending. Moreover, a preliminary study on a similar system has highlighted several issues that we will take into account in further development: (1) the limitation of the workspace may restrict the syringe motion in the virtual environment; (2) the ergonomic aspect of the haptic interaction we propose may be critical, as it has been documented that dental experts tend to prefer interacting through a device that remains familiar to them, such as a syringe [CTN13] [CdSNT14].

Future developments might also include migrating our haptic training system to a game engine like Unity3D (http://unity3d.com/) enhanced with a specifically designed haptic plug-in.

Acknowledgements

The authors thank Dr. John McClean for helpful discusions on the brain aspects. Dr. Anna Lysakowski was supported by a Fellowship from the US-UK Fulbright Commission.

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