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Exploration of temporal bone anatomy using mixed reality (HoloLens): Development of a mixed reality anatomy teaching resource prototype

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ABSTRACT

Mixed reality (MR), a technology which supplements the real world with virtual objects, is increasingly becoming available as a teaching tool in medical education. The Microsoft HoloLens device allows operators to experience MR using a head-mounted device without interfering with their physical reality, stimulating a realistic learning experience using virtual objects. This project aimed to develop a MR anatomy teaching application with HoloLens for exploring the anatomy of the temporal bone. The educational application was developed from a multidisciplinary collaboration between undergraduate and postgraduate students across several academic disciplines with Medtronic, a medical technology company. 3D anatomical models were built using ZBrush and Blender, while the HoloLens1 application was developed using Windows 10, Visual Studio 2017, Unity and Mixed Reality Toolkit (MRTK). Modules developed within the application included a basic HoloLens tutorial, a virtual temporal bone with surgical anatomy landmarks and free drilling of the temporal bone. The basic tutorial allows the operator to adapt to the MR environment prior to exploring the anatomical landmarks of the 3D temporal bone. The free drilling of the temporal bone using vertex displacement and texture stretching replicates a real-time bone drilling experience and allows the operator to explore the anatomical relationship between different otological structures.

Keywords: Temporal bone, Surgical, HoloLens, Mixed reality, ENT, Educational Tool.

INTRODUCTION

In undergraduate anatomical education, cadavers remain a major component of teaching (Moro et al., 2017). However, supervisory, financial and time constraints often limit the anatomy learning experience of postgraduate surgical trainees (Moro et al., 2017). Anatomy knowledge in otology is best acquired by dissecting cadaveric temporal bones (Weit et al., 2009) but the limited availability of cadaveric temporal bones may limit anatomy learning (Suzuki et al., 2004; Naik et al., 2013). Lack of anatomy knowledge among surgical trainees reduces surgical competency and often compromises patient safety during surgery (Tibrewal, 2006).

In the field of otolaryngology, temporal bone anatomy forms one of the main components of anatomy teaching. The 3D representation of temporal bone anatomy is complex in nature due to the numerous bony canals of the labyrinths and the tortuous course of the facial nerve (Reisser et al., 1996). The conventional approach of learning anatomy using textbooks illustrates the anatomy of the temporal bone in two-dimensional (2D) views, but this approach limits the visualisation of the complex anatomical structures in relation to one another. A combination of several modalities, such as 3D temporal bone surgical simulators and cadaveric temporal bone dissection, have been suggested for optimal anatomy teaching (Weit et al., 2019).

Three-dimensional (3D) visualisation technologies are increasingly used to augment anatomy curricula and improve understanding of complex spatial relationships inherent in the human body (Hackett et al., 2016; Nicola et al., 2018). Virtual reality (VR) is an example of 3D visualisation technology used to explore these complex relationships in anatomical education (Izard et al., 2017). The 3D virtual anatomical models are often constructed with radiological section images obtained through computed tomography (CT) or magnetic resonance imaging (MRI) (Izard et al., 2017). These constructed virtual images can be manipulated within the generated virtual environment to allow users to learn different anatomical structures while simulating a realistic surgical intervention (Izard et al., 2017). For example, the development of a virtual cerebral ventricular system using a MRI based computer model allowed users to explore the spatial orientation of the cerebral ventricular system and its relation to adjacent neural anatomical structures in a classroom setting (Adams et al., 2011). Another example is the Voxel-Man TempoSurg simulator, a commercially available temporal bone surgical simulator and dissector commonly used in otologic training programs (Arora et al., 2012); it allows realistic handling of surgical drills by trainees, which lets them understand the surgical anatomy of the temporal bone and various surgical approaches. The usefulness of this VR simulator as a teaching resource has been validated several times for realism across several domains (e.g. appearance of anatomical structure, appearance and performance of drill, depth perception and quality of graphics) and it was shown to complement traditional teaching methods well (e.g. temporal bone dissection) (Arora et al., 2012; Varoquier et al., 2017) and improve acquisition of technical skills and confidence by surgical trainees (Francis et al., 2012; Nash et al., 2012; Locketz et al., 2017). Despite displaying realism in the domains mentioned above, the VR simulator lacked elements of realism in other domains, such as drill ergonomics and haptic feedback (Arora et al., 2012). Interestingly, this surgical simulator is also capable of providing accurate teaching feedback to trainees, reducing the need for supervision and evaluation by surgeons (Zirkle et al., 2009). Another example of VR in anatomy education was the development of a virtual 3D temporal bone model for neurosurgical training by Morone et al., (2018). The model contained accurate neuroanatomical structures and was perceived to have improved surgical efficiency and safety if viewed by neurosurgery trainees prior to surgery. The application of

VR in anatomical education is not limited to temporal bone anatomy and neuroanatomy (Hendricks et al., 2018), but has also been applied to other fields of medicine, such as cardiovascular medicine (Silva et al., 2018). Several institutions (Henn et al., 2002; Erolin et al., 2019; Maresky et al.,2018; Marks et al.,2017; Moro et al.,2017) have also used VR technology to engage students with virtual models. Students found that the immersive VR technology highlighted the 3D relationship and size differences between anatomical structures well (Maresky et al., 2018). Similarly, Jones et al. (2005) also suggested that haptic feedback can be a valuable tool to explore and conceptualise complex shapes in haptic augmented and VR applications.

In contrast to VR, augmented or mixed reality (MR), a technology which supplements the real world with virtual objects, is a new teaching modality increasingly available in medical education (Barsom et al., 2016). Augmented reality or MR technology allows technologists to superimpose digital information onto real world objects to enhance user experience. This technology can be utilised for anatomical education by overlaying the digital information on to human cadavers or other physical anatomical models (Hackett et al., 2016). In contrast to VR, which fully immerses the operator in the virtual object and blinds them to reality, MR blends the virtual object into physical reality, providing a reality-virtuality continuum (Milgram et al., 1994).

Newly developed MR applications have already been introduced to operators with the aim of simulating an interactive learning experience (Herron, 2016). However, these tools are poorly accepted by operators, possibly due to their technological complexity as educational tools (Herron, 2016). The recent invention of HoloLens by Microsoft allows the operators to experience MR using an untethered head mounted device without interfering with their physical reality, simulating a realistic learning experience using virtual objects (Herron, 2016).

In contrast to VR, the MR technology by Microsoft HoloLens enhances the learning experience of the operators by causing negligible symptoms of simulator sickness (Vovk et al., 2018). If explored efficiently, MR has the potential to provide a contextual learning experience, allowing the operator to explore the complex 3D structures of a virtual model coexisting in the real world (Zhu et al., 2014).

Although cadaverless anatomy teaching modalities, especially VR and MR, have recently gained popularity for simulation of an interactive learning experience for operators (Zhu et al., 2014), a MR anatomy teaching tool using the Microsoft HoloLens is relatively novel, especially for temporal bone anatomy in otolaryngology.

This study aimed to develop a MR anatomical teaching application using a multidisciplinary approach with HoloLens to explore the 3D anatomy of the temporal bone. The educational HoloLens application aimed to allow the operator to explore the 3D anatomy of the temporal bone in physical space from different angles and planes prior to performing simulated temporal bone dissection of a virtual, synthetic or cadaveric temporal bone.

MATERIALS AND METHODS

The MR temporal bone anatomy teaching application was developed from a collaborative effort between undergraduate and Master of Science Degree (MSc) students from various academic disciplines at the University of Dundee (e.g. anatomy, computing science, forensic art & facial identification, medical art & medicine) and Medtronic, a medical technology company. The temporal bone MR application was developed in collaboration with a head and neck surgeon involved with the national ENT curriculum for surgical trainees (ISCP, 2018). The ENT curriculum requires trainees to understand the detailed anatomy of the temporal bone, practise operating using surgical simulators and then physically drill cadaveric temporal bones in a laboratory setting.

Surface scans (taken using an Artec Space Spider structured light scanner) of Adam,Rouilly plastic models of the temporal bone and a micro CT scan of an adult male skull (a specimen >100 years old from the Dundee Dental School, taken by Dr. Erolin using a Nikon XT H 225ST microCT scanner) were used to develop an anatomically accurate temporal bone model. The scans were imported into Zbrush (Version 4R8, Pixologic, Los Angeles, CA, United States) where they were used as 3D templates to allow medical artists to create an accurate model. The micro CT scanner has a 2000 × 2000 pixel flat panel detector, measuring 400 mm × 400 mm in size, which is positioned 1130 mm away from the source. This means that for very small specimens, a resolution of a few µm can be achieved. However, for larger objects, as in the case of this skull (up to 250 mm in diameter, moved closer to the detector to fit in the frame), this drops to around 125 µm. The model was created by a medical artist (rather than simply using the original scan data) to ensure a tidy mesh was retained, allowing for a low poly version to be exported later without issue. This was important for maximising the application's performance due to the limited computing power of the HoloLens. In addition, the medical artist sculpted several anatomical features directly in Zbrush, including the facial nerve, middle and inner ear structures. Blender (Version 2.79b) was used to create a basic head and neck model into which the anatomical structures could be placed. This acted as a useful orientation aid at the beginning of the application.

The temporal bone and other anatomical structures were created as separate subtools within Zbrush, and as such they required manual assembly in Unity. The anatomical accuracy of the final temporal bone model and other anatomical structures were verified by several anatomists and otolaryngologists involved in the project. Unity (version 2017.1.1f1, Unity Technologies ApS., San Francisco, CA, MRTK (Mixed Reality Toolkit) (version 2017.1.1) and Microsoft Visual Studio 2017, (version 2017.14, Microsoft Corp. Redmond, WA) were used to develop the entire Universal Windows Platform (UWP) application for HoloLens 1.

After designing the temporal bone model prototype, the model was tested informally with the project team members and otolaryngologists for feedback. The users highlighted the need for a tutorial as the majority of users were unfamiliar with the new MR technology and the HoloLens interaction system. In order to provide a pleasant MR experience for the users, a set of tutorials was developed using Unity to provide users of all abilities with the necessary skills to use the device and application so that they could explore the virtual temporal bone. The specifications and content of the tutorial were identified by the project team members using the informal feedback, and the set of tutorials was designed to cater for the function of the temporal bone model prototype (Results: Module 1: Basic HoloLens Tutorial). In an iterative process of designing, developing and informal testing, a set of tutorials was developed within the HoloLens using Unity to provide users with the necessary skills to use the MR application to explore the virtual temporal bone.

In order to simulate a bone drilling experience, the authors had the following options to choose from. First, a voxel based approach (i.e. a 3D pixel or volumetric pixel model) (Chen et al., 2008), where voxels that come into contact with the drill are destroyed or the shader surface deformation technique (Correa & Silver., 2007) that consists of vertex displacement and texture stretching (Picinbono et al., 2003) were considered. Due to computing power constraints, the authors opted for the latter technique. The shader surface deformation technique was subsequently developed using Unity and Visual Studio to simulate a virtual bone drilling experience. When the user moves the drill into the bone, the algorithm computes the area and distance to be deformed, as well as the direction of the displacement.

However, this process also stretches the texture and causes it to look unrealistic. To make it look more realistic, a Perlin noise function was used. The Perlin noise function interpolates the original colour and white between the displaced vertices by computing the dot product of pre-defined gradient vectors and the vertex in question (Figure1a). This technique outperforms the constant noise technique shown in Figure 1b. A limitation of this method is that this gradually depreciates visual accuracy; to counteract this, several planes mimicking the trabecular appearance of bone were inserted. As the drill penetrates deeper, the surface is pushed behind the planes, which then becomes the new surface until it vanishes behind the subsequent plane. This achieved a sense of depth and realism.

RESULTS

Modules successfully developed in the HoloLens application included: (1) Module 1: a basic HoloLens tutorial; (2) Module 2: an anatomy model showing virtual temporal bone with anatomical landmarks, and (3) Module 3: a free drilling experience of the temporal bone. The modules are available in a video format in Supplementary Video 1.

Module 1: Basic HoloLens tutorial

Given that the HoloLens was a very new technology, the tutorial was designed to allow the user to adapt to the MR environment and teach them the device’s controls. In this module, the operator learns to utilise the cursor function (Figure 2a and Supplementary Video 1) and how to select different anatomical structures highlighted in the temporal bone in subsequent modules. The operator is also able to move the cursor with a rotational head movement (Figure 2b and Supplementary Video 1) to view the anatomical structures from various angles and planes. This ensures that the HoloLens device is fitted properly on the operator’s head and that all the virtual models are in the field of view. The final tutorial requires the operator to drag an object towards a target (Figure 2c and Supplementary Video 1). This provides the practical experience needed to use the surgical drill during free drilling of the temporal bone in Module 3.

Module 2: Temporal bone surgical anatomy exploration

The second module allows exploration of the surgical anatomy of the whole temporal bone. The operator can view the virtual temporal bone model in a realistic 3D space using a plane or cross-sectional view (Figure 3 and Supplementary Video 1). The 3D view allows the operator to orientate and understand the anatomical relationships between various structures. For example, the suprameatal spine of Henle (Supplementary Video 1) is an important surgical landmark for mastoidectomy; the operator is able to explore its relationship to other structures prior to drilling. The sigmoid sinus is another important surgical landmark in skull base surgery and the operator can visualise this deep structure from different angles and planes before drilling (Figure 3c and Supplementary Video 1). The list of anatomical landmarks and anatomical details incorporated into the MR temporal bone model are listed in Table 1.

Module 3: Free drilling of the temporal bone

The free drilling of the temporal bone developed using the shader surface deformation technology (Correa & Silver., 2007) aimed to replicate a real-time bone drilling experience and allows the operator to explore the anatomical relationship between superficial and deep otological structures in a surgical plane (Figure 4 and Supplementary Video 1). This module simulates a cadaveric bone drilling experience for the operator, who can then practise temporal bone surgical procedures (e.g. mastoidectomy) at his/her own pace. Different drill sizes and drill aggressiveness options are also available for simulating different drilling experiences. In addition, the trabecular texture of the bone and mastoid air cells, designed using artistic software, aimed to simulate a cadaveric bone drilling experience. The facial nerve and sigmoid sinus are also highlighted in relation to other anatomical structures when the operator drills deeper into the temporal bone. These two structures form important surgical landmarks in otology and are thus highlighted in red if damaged during drilling. Overall, this module allows the operator to deform the temporal bone using the virtual drills and also aids the operator's understanding of the delicate anatomical structures in a 3D MR environment.

DISCUSSION

This study demonstrated the development of a MR temporal bone surgical anatomy educational application using a collaborative multidisciplinary approach between several academic disciplines. The sharing of knowledge and skills between the members of the interdisciplinary team facilitated the development of a novel teaching tool that aims to let users learn complex anatomical structures of the temporal bone in an interactive manner using the MR technology.

Since a combination of several modalities such as 3D temporal bone surgical simulators and cadaveric temporal bone dissection have been suggested for optimal anatomy teaching (Weit et al., 2009), this educational tool aimed to supplement anatomy knowledge gained through 2D images from anatomy textbooks. It has the potential to bridge the knowledge gap between textbook learning and 3D temporal bone surgical simulators. In addition, the development of anatomy resources using 3D visualisation technologies has been primarily focused on VR such as the Voxel-Man TempoSurg simulator; this temporal bone model prototype highlights the potential of MR for future development of anatomy teaching resources.

The complex 3D representation of temporal bone anatomy with the numerous bony canals of labyrinths and the tortuous facial nerve is best acquired using a model with spatial representation. This MR application introduces another teaching modality which allows the operator to orientate, navigate and understand the complex 3D bony and soft tissue anatomy of the temporal bone. The operator is also able to walk around the bone model which is suspended in the real world, viewing it from various angles and planes. More importantly, the model can also be placed in a surgical plane so that the operator can explore the anatomical structures as if dissecting in a surgical environment, which is more realistic and clinically relevant than anatomy textbooks. Free drilling of the temporal bone also provides flexibility when compared to cadaveric bone dissection, allowing operators to view the deep anatomical structures of the temporal bone (e.g. facial nerve) at their own pace from different perspectives. For example, operators can undo drill functions and rectify their mistakes instantly if an error is made, which is impossible in cadaveric bone dissection.

MR anatomy teaching applications are constantly being developed and updated with advancement in MR technology over time. Previous innovative efforts by the Case Western Reserve University in Cleveland highlighted the potential of MR technology in exploring the gross anatomy of the human body (Case Western Reserve University, 2018). The 3D MR anatomical images developed by the Cleveland group can be manipulated using gestures, gaze and hand commands. In addition, operators at a remote location can view the same image as those in the central location and interact with them. Another related prototype is the LINDSAY anARtomy application developed using META 1 SDK (Tworek et al., 2012;

Lindsay, 2018). In this application, various virtual body systems (e.g. cardiovascular and musculoskeletal) can be separated and the virtual models can be viewed in real space using META glasses. QR code markers can also be placed on the user's body such as the forearm; virtual models will then be generated to overlap with the user's own forearm. In otolaryngology, the application of MR is growing for preoperative planning, navigation, treatment and diagnostic purposes (Wong et al. 2018), but the application of MR for anatomy education is rather limited. To date, the study by McJunkin et al. (2018) is the only published study describing the development of a 3D temporal bone model using MR which can be overlaid on physical models (e.g. cadaveric skull) to guide skull base surgery and temporal bone dissection. The research group developed a MR application to visualise the temporal bone structures and highlighted that their application is a highly accurate image guidance system for anatomical dissection and lateral skull base surgery (McJunkin et al., 2018). In contrast to the study by McJunkin et al. (2018), our MR prototype is an interactive anatomy teaching tool which was predominantly designed to explore the spatial relationships of the anatomical structures of the temporal bone outside anatomy laboratories and surgical theatres. Previous efforts were also predominantly focused on the gross anatomy of human organs (e.g. heart, lungs and limbs), while in the present study, the authors primarily focused on the complex 3-D anatomical structure of the temporal bone. The study is also the first to incorporate a MR bone drilling experience.

There are several limitations to the model and MR technology in general. This prototype demonstrated that bone drilling can be simulated using the MR technology but needs to be developed further to simulate realistic drilling. The models used in this application could only be drilled from a single direction due to the combination of using a low detail 3D model to satisfy the computing power constraints and the shader surface deformation technology. In the shader deformation technique, the vertices were only allowed to be displaced in a single direction, as multi direction displacement would result in long edges (i.e. gaps) which would prevent the vertices from interacting with the drill, making the model not drillable. However, if more computing power was available, a higher resolution 3D model with more vertices could be used to provide a better drilling experience. A voxel temporal bone model (i.e. a 3D pixel or volumetric pixel model) incorporated into the MR environment may provide a better drilling experience. Despite being one of the most advanced MR systems available, the HoloLens has limited computing power, as with any other mobile device. Hence techniques such as detail reduction of 3D models are necessary in order to allow applications to run smoothly (Schied et al., 2018). More detailed and realistic applications are likely to become possible with the improvement in MR technology over time. Furthermore, the temporal bone model does not include the complete anatomical structures of the temporal bone (e.g. arterial supply to the inner ear). Incorporation of other important deep surgical landmarks are rather challenging due to the limited processing power of the HoloLens. The structures can be better modelled with the advancement in MR technology; the model is continuously being developed as the technology progresses to simulate a real temporal bone drilling experience for the user.

Although the shader surface deformation simulates a real-time bone drilling experience, MR technology does not yet support haptic feedback, so the drilling precision and control may vary significantly when compared to cadaveric temporal bone dissection. The scale and magnification of this prototype may also differ from an actual temporal bone and does not account for individual anatomical variation. The dissection error margin is also greater when compared to dissecting a cadaveric temporal bone, which requires fine psychomotor skills. The magnified bone without haptic feedback support in the present model may affect the development of fine psychomotor skill needed for physical temporal bone dissection. Haptic feedback devices such as the Geomagic Touch 3D system have been popular candidates for mastoidectomy exploration in recent years (Andersen et al., 2015; Andersen, 2016; 3D Systems, 2018). The haptic feedback in VR provides a realistic bone drilling experience for the user and VR technologies have been shown to be effective in increasing cadaveric mastoidectomy performance; skills acquired from VR simulations are transferable to the traditional dissection setting (Andersen et al., 2015; Andersen., 2016). Previous studies have also used pre-operative medical image data from patients to simulate a virtual temporal surgical environment using haptic feedback (Chan et al., 2016). The virtual temporal bone surgical environment using haptic feedback simulates a realistic operating environment whereby the surgeon can readily observe the correspondence between surgical exposure, anatomical exposures and the location of pathology to the intra-operative video (Chan et al., 2016). Although high-fidelity haptic feedback improves surgical performance among trainees, this technology is primarily focused on VR temporal bone simulators (Fang et al., 2014). Interestingly, a study by Hochman et al. (2014) described the initial stages in the development of a MR temporal bone surgical dissector using haptic feedback. In the future, incorporation of haptic feedback in MR may provide an added advantage to the HoloLens for a realistic bone drilling experience for developing the same psychomotor skills acquired in VR simulation (Lopes et al., 2018; Holo-Stylus, 2018).

In order to develop and improve the application further, we tested the application informally with a group of otolaryngologists. Overall, the prototype was well received and the responses of the informal feedback were largely centred around the unsuitability of the free drilling module as a teaching tool in practice. After using the application, the otolaryngologists reported that the drilling module was difficult to use and less user friendly. It was suggested that the drilling module was not true to life and the addition of haptic feedback either by using a physical drill or via Bluetooth would improve the bone drilling experience. It was also noted that the temporal bone model presented in the application was non-pathological and the addition of models with variable anatomy and pathology would be a welcome addition to the training of surgical trainees. The other modules including the surgical anatomical landmarks were well received overall. Potential for development of screen sharing for telemedicine and surgical teaching sets the HoloLens apart from already established VR simulators.

In the future, the authors aim to develop the application further to cater to the teaching needs of ENT trainees and to test this prototype application formally with the trainees. A test for realism and usability (e.g. anatomical and spatial representation of the temporal bone model, usefulness as a training tool and the appropriateness of visual and auditory feedback) (Koch et al. 2019) is important and a formal feedback from the otolaryngologists will allow the authors to improve the current prototype further. The authors plan to design the tutorial to cater specifically to the prototype (e.g. by incorporating a bone drill tutorial). In addition, the authors also plan to incorporate other relevant anatomical structures to the bone drilling experience (e.g. dura mater and arterial supply to the inner ear) as well as a shared learning experience, where tutors would be able to demonstrate their knowledge to multiple operators simultaneously and provide instantaneous feedback.

CONCLUSIONS

In conclusion, this educational tool provides an interactive learning experience for operators to explore the complex anatomy of the temporal bone using a virtual model incorporated into their physical space in the real world. The MR technology provides exciting new methods for learning complex surgical anatomy while ensuring patient safety. This MR application is a prototype and serves as a blueprint for future development of MR anatomy teaching resources using a multidisciplinary approach.

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